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A PETROTECTONIC ANALYSIS OF CLEAVAGE IN OTHERWISE UNMETAMORPHOSED SEDIMENTS

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ABSTRACT

A petrofabric analysis of the widespread cleavage in the Moccasin member of the Lowville formation in western Virginia has shown the presence of a relict sedimentary quartz fabric, corresponding to the sedimentary fabric of beds without cleavage, along with a quartz fabric girdle about *B*. This condition has been interpreted as indicating an incipient stage of metamorphism which developed cleavage in the Moccasin and not in adjacent members because the cleaved incompetent beds of the Moccasin are composed of quartz grains of widely different sizes surrounded by large amounts of calcite and clay, the whole being intimately mixed and completely unassorted. Several possible interpretations of the mechanical processes involved in the formation of the cleavage are considered.

INTRODUCTION

While working with Dr. A. A. L. Mathews on the areal geology of Giles County, Virginia, for the Virginia Geological Survey in the summer of 1933, the writer became interested in the cleavage problem discussed in this paper. Here, in a region of no intense metamorphism but with considerable folding, there occurs one horizon in which cleavage is everywhere developed.

In making this investigation, an attempt has been made to determine the effect of grain size and the effect of immediate mineralogical environment on the final orientation of the quartz fragments scattered throughout the rock and to determine, if possible, why this horizon alone has consistently developed cleavage. From a syste-

matic determination of the quartz fabrics representing the several environments, it has also been possible to draw certain conclusions on the relative importance of shear and rotation in the development of the cleavage and on the homogeneity of the rock's failure.

AREAL GEOLOGY

In Giles County, Virginia, the exposed geological section extends from the Middle Cambrian through the Mississippian. The struc-

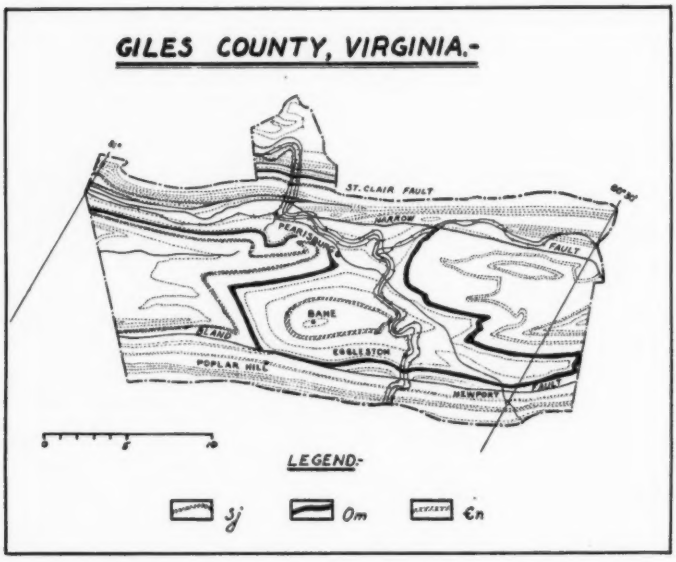

FIG. 1.—*Sj*, Juniata formation; *Om*, Moccasin member; *€n*, Nolichucky shale

tural high of the county is an elliptical dome, in which the Cambrian is exposed (*€n* on the map, Fig. 1) near the town of Bane. To the southwest, the structure opens into a broad syncline, on which are several anticlines trending parallel to the northeast-southwest regional structure. North of Bane, an arch in this syncline joins it with a similar but broader syncline in the northwest part of the county. Three large overthrust faults parallel the regional strike and dip to the southeast, so that the overthrust blocks are, in effect, like

shingles on the southeast side of a roof, the ridgepole of which trends northeast.

In an area of such structures, jointing and shattering are to be expected and are seen almost everywhere. One horizon, the Moccasin member (*Om* on the map),[1] of the Lowville formation of the Black River group, habitually exhibits well-developed cleavage, the strike and dip of which is everywhere nearly parallel to the axial plane of the fold on which the cleavage occurs. This development of cleavage is so universal that it serves as an excellent horizon marker in mapping the area. However, the best development occurs in a narrow belt about 30 miles long on the underthrust side of the Bland fault. This belt extends northeast from Poplar Hill, passing south of Eggleston, to a point about 5 miles northeast of Newport. In this belt the Moccasin is always folded into tight, almost isoclinal folds, in which most of the bedding planes have been obliterated by the development of cleavage and can be seen only by differential weathering or along the contact between two different kinds of rock.

The Moccasin is made up of interbedded sandstone and gray and red mudrock. Except for the color difference the mudrocks are alike and contain varying amounts of detrital quartz, exceedingly fine-grained calcite, and micaceous clay. The grains of the sandstone vary in size from about 20 microns to 2 millimeters. Cleavage has developed in the mudrock. The sandstone, however, has failed in tension or lift joints and occasionally by small overthrusts near the crests of folds. Almost all fractures, except the overthrusts and cleavage, have been completely or partially filled by calcite.

THE SPECIMENS

In the small fold shown in Figure 2 the rock types of the Moccasin are well represented. At the lower center is a mass of mudrock (*M*) in which the bedding is almost obliterated and cleavage is well developed. Immediately above this lies a thin bed of sandstone. At the top and center of the picture is another bed of mudrock (*SM*) which has many sandy layers in it. This bed has also developed cleavage. Above this sandy mudrock and visible on either side of the

[1] Modified after Charles Butts, "Geologic Map of the Appalachian Valley of Virginia and Explanatory Text," *Virginia Geol. Surv. Bull. 42* (1933), pp. 18–19 and pocket.

picture is a thick bed of coarse-grained sandstone (*SS*) broken by tension or lift joints. It should be noted that the rocks adjacent to the tension joints, as well as the beds at the crest of the fold, are well separated. This fact, as well as thickening at the crest and thinning on the limbs, removes all possibility of its being a shear or slip fold, as used by Knopf and Ingerson[2] to signify a fold formed entirely by shear or slip without flexure.

The rocks to be considered fall into three groups: sandstone (*SS*), sandy mudrock (*SM*), and mudrock (*M*).

FIG. 2.—A typical fold in the Mocassin showing cleavage in the mudrock at the center and tension joints in the sandstone at the sides. The axial plane is tilted about 30°. *SS*, sandstone; *SM*, sandy mudrock; *M* mudrock.

THE SANDSTONE

Figure 3 represents a typical section of the sandstone. The larger grains vary in diameter from $\frac{1}{2}$ to 1 millimeter, and the smaller from $\frac{1}{4}$ to $\frac{1}{2}$ millimeter. Scattered throughout the section are grains of a former quartzite (Fig. 4) which had a well-developed orientation. There are also many quartz grains, like the one near the center of Figure 3 and enlarged in Figure 5, which contain purple vermicular chlorite. A few feldspar grains also occur. The quartzite pebbles, the chloritic quartz, and the feldspar occur in the mudrocks as well as in the sandstone. Their abundance and distribution suggest a possible common source for all three types.

SANDY MUDROCK

In thin section this member should be divided into shear zones and lenses. As illustrated in Figure 6, the lenses (*L*) generally con-

[2] E. B. Knopf and Earl Ingerson, "Structural Petrology," *Geol. Soc. Amer. Mem. 6* (1938), p. 157 and Fig. 3*c*.

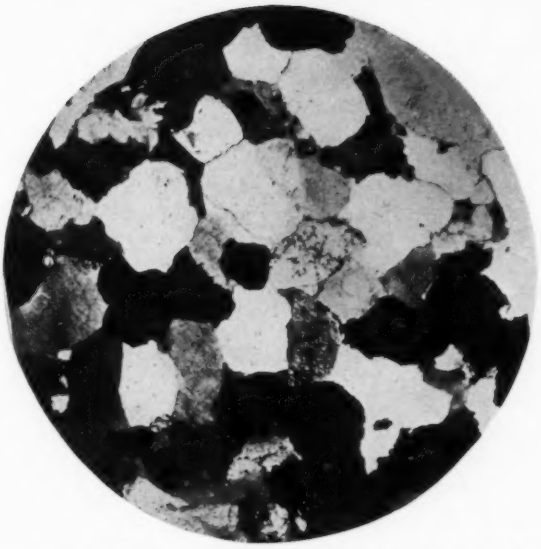

FIG. 3.—Typical photomicrographs of quartz grains in the sandstone (×19). Crossed nicols.

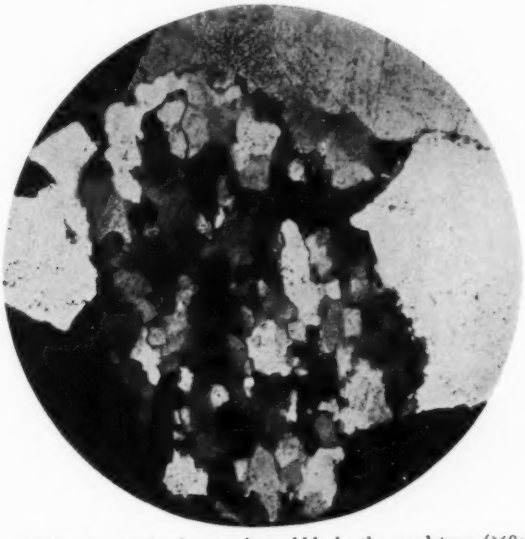

FIG. 4.—Photomicrograph of quartzite pebble in the sandstone (×80). See also Fig. 11. Crossed nicols.

FIG. 5.—Quartz grain with purple vermicular chlorite seen in the center of Fig. 3 (×150).

FIG. 6.—Photomicrograph of the sandy mudrock showing alternate shear zones (*S*) and lenses (*L*). (×19.) *Q*, quartz.

sist of very angular quartz grains from $\frac{1}{4}$ millimeter to almost submicroscopic size, with the coarser grains seldom separated from one another by more than two diameters. These quartz grains are in a matrix of exceedingly fine-grained calcite mixed with a red micaceous clay. The shear zones (*S*) differ from the lenses in that they have more clay and less calcite. Each grain of quartz in a shear zone is adjacent to a visible line along which movement has occurred. The effect is a distinct linear arrangement. These grains tend to be less than half the size of those of the lenses and are often quite widely separated from one another.

MUDROCK

In composition, the mudrock differs from the sandy phase in having less quartz, as well as an occasional large calcite grain (*C*) in a matrix of much finer calcite, along with distinctly elongated masses of ferruginous micaceous clay (*F*). The large calcite grains generally have one cleavage or parting which has been broken open (see Fig. 7). The quartz is scattered throughout the rock, but it occurs in greatest concentration in lines subparallel to the cleavage. This latter, and the elongated ferruginous clay, may be seen in Figure 8.

THE ANALYSES[3]

The specimens used here were collected after painting the strike and dip on the surface of each. The exact co-ordinates were written on the painted surface. Since the co-ordinates of the structure were known, it was a simple matter to locate any desired plane or line by means of a spherical projection and a two-circle goniometer, or with the device designed by Ingerson.[4]

In order to establish a relation between the final orientation of the minerals present, several specimens were collected where the

[3] The following references contain clear presentations of the theory and methods of petrofabric analysis: Bruno Sander, *Gefügekunde der Gesteine.* (Vienna: Julius Springer, 1930); E. B. Knopf, "Petrotectonics," *Amer. Jour. Sci.*, Vol. XXV (1933), pp. 433–70; James Gilluly, "Mineral Orientation in Some Rocks of the Shuswap Terrane as a Clue to Their Metamorphism," *Amer. Jour. Sci.*, Vol. XXVIII (1934), pp. 182–201; H. W. Fairbairn, *Structural Petrology* (Kingston, Ont.: Queen's University, 1937 [mimeographed]); John C. Haff, "Preparation of Petrofabric Diagrams," *Amer. Min.*, Vol. XXIII (1938), pp. 543–73; Knopf and Ingerson, *op. cit.*

[4] E. Ingerson, "Accurate Orientation of Thin Sections," *Amer. Min.*, Vol. XXII (1937), pp. 760–72.

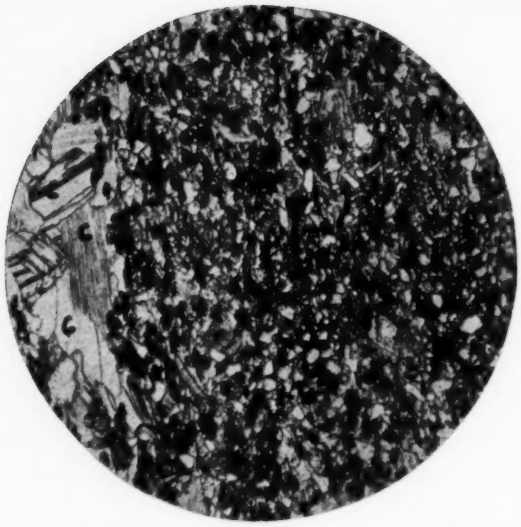

FIG. 7.—Photomicrograph of the mudrock showing several large calcite grains (*C*). (×19.)

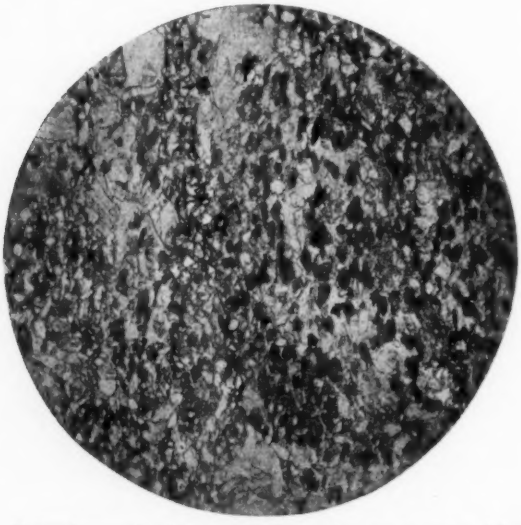

FIG. 8.—Photomicrograph of the mudrock showing quartz grains (*Q*) strung out along lines and elongated masses of micaceous clay (*F*). (×19.)

cleavage and the jointing occurred within a few inches of one another. Also, in several specimens collected from the anticline pictured in Figure 2, a gradation in the amount and grain size of the detrital quartz in the mudrock was obtained.

In making analyses from these specimens, only quartz and calcite were considered. Three general types of orientation are possible for each of these minerals: (1) they may be oriented so that the elements of the space lattice of each grain are nearly parallel (this was investigated with X-rays); (2) they may be oriented so that the positions of the optic axes of all the grains of any particular mineral form a statistical pattern (this was determined on the universal stage); and (3) cleavage planes and fragmental shapes may also show statistical relationships (this was studied with the universal stage and photomicrographs).

Each section investigated was cut in the plane perpendicular to the strike of the cleavage, which is also perpendicular to the *B* axis of the strain ellipsoid and the *b* fabric axis. Since the cleavage was plainly visible in almost every section, each section was marked with the direction of the vertical, which furnished a means of correlation between sections and a measure of the departure from the vertical.

The analyses were made by measuring, on a universal stage, the relation of the spatial position of the *c* axes of quartz grains to the *B* axes or strike of the cleavage. The data thus obtained were plotted on an equal-area projection net. A circle whose area represented one one-hundredth of the total area of the net was used in counting the points.

In each diagram the contour interval represents the presence of one determination per 1 per cent of area. All contours, including the zero contour, are shown. The small lines at the top and bottom of each diagram represent the position of the vertical. The two dots indicate the direction of the cleavage.

THE DIAGRAMS

SANDSTONE

Since the coarse-grained sandstone does not show cleavage, it was chosen to determine whether there was an original fabric (orientation) in the sediments before the formation of the cleavage. At the

same time the jointing of the sandstone illustrated in Figure 3 was investigated. A section was cut adjacent to one of these tension joints perpendicular to the strike of the structure and the cleavage. The orientation of every grain within an approximately equidimensional area of 200 grains was measured. As each grain came under the objective, it was searched for evidence of recrystallization which might have obliterated the original fabric. Although a few grains

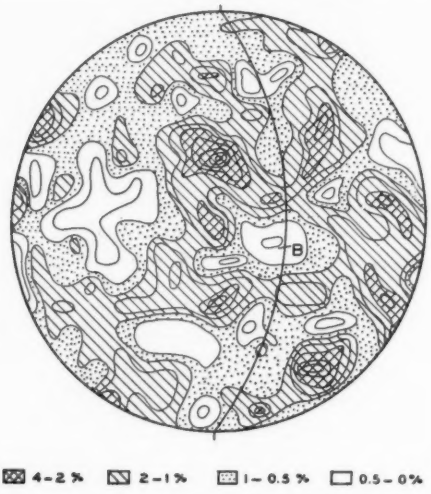

FIG. 9.—Two hundred quartz *a* axes from the coarse grained sandstone

showed wavy extinction, the majority were quite sharp in extinction and in outline. The presence of vermicular chlorite and of many grains of an earlier quartzite constitutes strong evidence against recrystallization.

As shown by the offset *B* axis, Figure 9, this section was cut somewhat off center. Figure 10 is the same diagram with the *B* axis rotated to the center. Although there are a number of points strewn over the diagram in the zone of 1–2 per cent, the several maxima lie clustered in an elliptical arrangement from 20° to 40° from the *B* axis and are greatest in a line passing through *B* and the four to five o'clock position. The majority of the grains from which this diagram

was made are inequidimensional and some are oblong. Similar diagrams have been interpreted as showing a sedimentary orientation in which the oblong grains as well as those making up the maxima lie with their optic axes approximately parallel to the planes of motion in the sedimentary medium.[5] Thus the sandstone may be said to have a sedimentary orientation which has not been confused by the forces which caused the jointing.

FIG. 10.—Same as Fig. 9 with *B* axis rotated to center

In Figure 11 the diagram is made up of 35 quartz axes from the pebble shown in Figure 4. This relic girdle of a former quartzite now lies near the *aB* plane (cleavage plane) of the new structure. In addition to indicating, along with the grain shown in Figure 5, the types of source material from which the quartzite was derived, pebbles of this type are interesting from another point of view. It has long been known that quartz has a differential hardness in different crystallographic directions and that abrasion of its surfaces is consequently related to its optic axis. In this pebble the prism posi-

[5] Sander, *op. cit.* Diagram 68, p. 314; No. 68, p. 293, and bottom of p. 201, Diagram 68.

tions are alined with the surface enclosing its least dimension. Recently Wayland[6] has shown that in at least two dimensions there is a close relation between the long dimensions of individual grains in the St. Peter sandstone and their optic axes. One may assume, therefore, that in some cases the optic axis of detrital quartz grains is near the position of the longest dimension of the grain.

FIG. 11.—Thirty-five quartz *c* axes from the pebble shown in Fig. 4

SANDY MUDROCK

The major point of interest in the sections of the sandy mudrock is the possible difference in orientation between the grains lying entirely in shear zones and those lying entirely in lenses. Two partial diagrams were made. In the first, Figure 12, only those grains which are surrounded by shear zones were chosen. In the second, Figure 13, the grains chosen lay entirely in lenses.

In Figure 12 the maxima are largest at the top and bottom of the diagram. On either side, smaller maxima occur nearly at right angles to a zone through the large maxima and *B* and are distinctly sep-

[6] R. J. Wayland, "Optical Orientation in Elongate Clastic Quartz," *Amer. Jour. Sci.*, Vol. CCXXXVII (1938), pp. 99–109.

arated. If the maxima represent stages in the failure and if they occur in pairs at approximately 90° from one another, then there have been at least two separate stages in the failure which oriented the quartz in these shear zones.

In Figure 13 there is a more even distribution of axes in a girdle. The maxima are not so well developed, and, although there is one

FIG. 12.—One hundred and eighty quartz *c* axes from the shear zone of the sandy mudrock.

maximum at the top of the diagram which is similar in position to one in Figure 12, the largest lies in the eight o'clock position on the girdle. While the same forces that distributed the maxima in Figure 12 have affected the quartz in the lenses, their effect has been less, and the diagram may be considered to be intermediate between that of the shear zones and those for the coarse-grained sandstone. This is further suggested by the presence of four submaxima arranged elliptically about 40° from *B*, which may be a relic of the sedimentary orientation of the sandstone.

Since all the data for these diagrams were obtained from selected grains, it was necessary to make another analysis to show the orien-

tation of every grain. Because of the difficulty of measuring each grain without repeating those already measured, each grain was recorded as measured on an enlarged photograph of Figure 14 and of adjacent areas. This analysis, Figure 15, shows a well-defined elliptical arrangement of maxima about 40° from the *B* axis, which is separated from an incomplete girdle by an area of few or no *c* axes. The central part of the diagram is very similar to the relic sedimen-

FIG. 13.—One hundred and fifty quartz *c* axes from lenses of the sandy mudrock

tary orientation of Figure 10 in the number of maxima and in the position of the largest maximum.

In the girdle the position of the maxima includes those of both Figures 12 and 13. If the relic sedimentary effect is removed, the diagram approaches the arrangement of a *B* or girdle tectonite and differs from such an arrangement in that its maxima are spread over a broader area. Incomplete dimensional and lattice rotation must have played a large part in forming this arrangement.

Although the combined selected data for the shear zones and lenses, as shown in Figure 16, are not nearly so complete, they compare favorably with those of Figure 15.

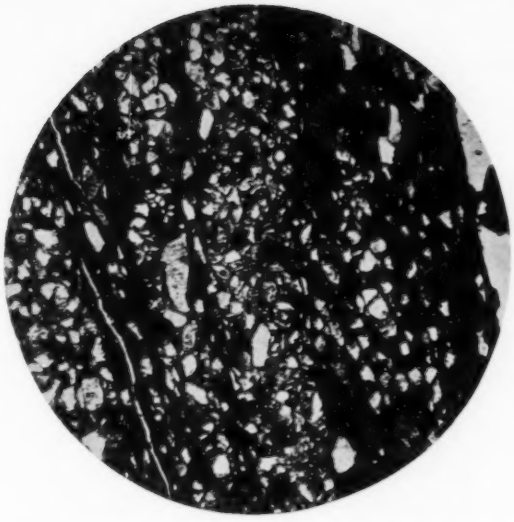

FIG. 14.—Photomicrograph of the area of the sandy mudrock from which every grain was measured (×19).

FIG. 15.—Four hundred quartz *c* axes from the preceding photograph

From the data which may be had from the photograph, Figure 14, the effect of two-dimensional grain size and shape on the final position of the optic axis was investigated. In Figure 17 the contours represent the concentration of optic axes of fifty elongated grains regardless of size. In general, they fall in the position of the maxima on Figure 15. At least the two-dimensional elongated shape does not appear to have controlled strongly the final position of the optic

FIG. 16.—Three hundred and thirty quartz *c* axes from the combined data of Figs. 12 and 13.

axes, although most of the axes lie near the zone of the cleavage. On the same diagram are plotted the axes of a number of superindividuals (grains much larger than the average) regardless of their shape. They show no marked difference from the average-sized grains in the position of the optic axis.

THE MUDROCK

Of chief interest in the mudrock is the orientation of the quartz grains which are strung out along lines which seem to be equivalent to the shear zones in the sandy mudrock. Important also is the orientation of the open planes in the large calcite grains. Figure 18 represents the axes of 200 quartz grains which lie in or along the

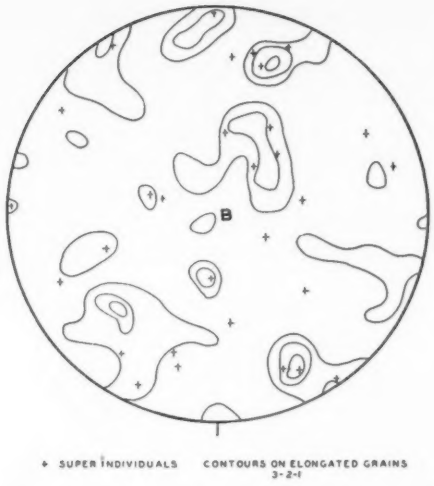

FIG. 17.—Contours for 50 elongated grains and location of superindividuals from the data of Figs. 14 and 15.

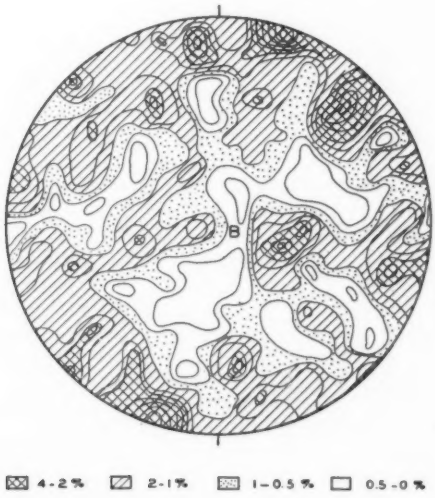

FIG. 18.—Two hundred quartz *c* axes from the mudrock. Only those grains lying in or adjacent to the linear arrangement shown in Fig. 8 were measured.

stringers in Figure 8. The two maxima zones of the girdle lie near the plane of cleavage. Around *B* there is again the suggestion of a relic girdle, although it is not too definite. The chief maxima of this relic girdle approximate the position already illustrated in Figures 9 and 15. Since the grains chosen for this diagram are in the position where maximum movement should have taken place, and since the shear-zone diagram has already shown a preponderance of axes lying

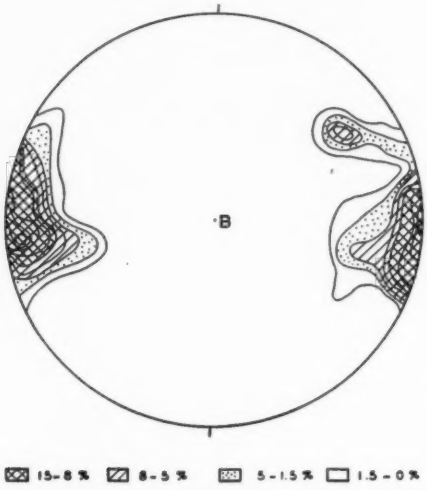

FIG. 19.—Poles to 60 calcite cleavages or lamellae such as those shown in Fig. 7

in the plane of the cleavage and subparallel to the directions of motion, the location of these maxima was to be expected if the failure in the mudrock took place on a more closely spaced system of shear zones and lenses.

In Figure 19 are plotted the poles to 60 calcite cleavages or lamellae. As can be seen from the photograph of Figure 7, these calcite grains are poorly defined. It was not possible to determine the *c* axis for the majority of them and therefore not possible to distinguish between lamellae and cleavage. The group of planes chosen was the most open in each grain. It should be noted, however, that, although the maxima lie near the edge of the diagram and in a posi-

tion almost perpendicular to the rock cleavage, there is no analogy of condition to diagrams of similar appearance for platy minerals. In Figure 20 an area corresponding roughly to that covered by either maximum of Figure 19 is ruled parallel. If the numbered points in this area are considered to be poles to calcite cleavages, the optic or *c* axis of the calcite falls 44°.6 from the points chosen and so on the small circles indicated. For the entire ruled area the optic axis may

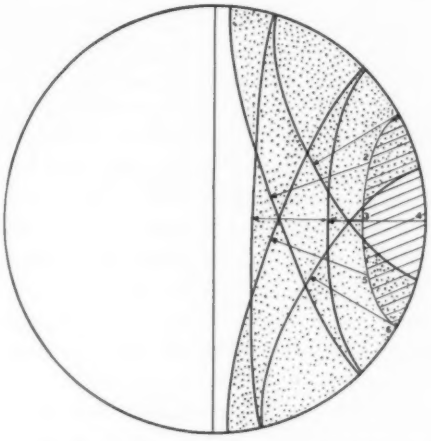

FIG. 20.—If the cross-ruled area represents poles to calcite cleavages, and the extremes of the area, such as the points numbered, have the position of their *c* axes plotted, then these lie anywhere on the small circles shown separated from the points by 44°.6. For the entire area the *c* axes may fall anywhere within the stippled area.

fall anywhere within the stippled zone. If the lamellae were chosen, the result would be similar except for a decrease in the angle (26°). This arrangement of the axes of Figure 20 is totally different from that of a diagram for a platy mineral whose optic axis or bisectrix would fall at or near the same point as the pole to the platy cleavage. For calcite, Figure 19 serves only to show that at least one plane in the calcite is nearly parallel to the cleavage of the rock and that movement has been sufficient to open that one plane.

Several X-ray photographs of oriented specimens of the mudrock failed to be of much value, since there is little of homogeneity in the

grain size. The pictures invariably showed large spots from larger grains and much fogging near the center, where the clay would best show its orientation, because of the presence of large amounts of free limonite. Lines for calcite and quartz can be distinguished, however, and they showed no lattice orientation.

SUMMARY

Three points are evident in a general survey of the quartz diagrams. There is clearly defined in Figures 10 and 15 a relic sedimentary orientation which can be seen less clearly in each of the other diagrams. In all the diagrams, except that of the coarse sandstone, there are well-defined maxima lying in a girdle about the *B* axis and each maximum is repeated in nearly the same position in several, but not in all, of the other diagrams. This suggests a homogeneity of deformation and failure.

In each quartz diagram, except Figure 10, there is a tendency for the maxima lying at the top and bottom of the diagram to cover the largest area and to contain the greatest number of points. The location of maximum density of the top and bottom maxima is within 15° of the vertical. The *c* axes seem to prefer a position subparallel to the line of motion in the plane of the cleavage, especially in the shear zones where cleavage is best developed, although a large number lie nearly perpendicular to this position.

CONCLUSIONS

In attempting to explain the process by which this cleavage was formed, two methods for the formation of the present quartz fabric must be considered. Assuming that the chief orientation of the quartz before deformation was that imposed by the sedimentary medium from which it was deposited and was located in a roughly elliptical fashion about 40° from the present *B* axis, the process must explain the partial destruction of this orientation and the formation of the new girdle. Did the forces of deformation simply move grains mechanically so that their axes fell outside the original orientation, or was the disruption an orderly one controlled by the strength of the deforming force, the friction encountered between grains, and the preferred directions of motion inherent in the grains themselves?

The first possibility seems to be denied by the presence of en-

circling minima between the relic fabric and the new girdle (Fig. 15) and the presence of corresponding maxima in diagrams from widely different parts of the same structure. Surely no random motion could consistently produce such an arrangement.

Proceeding on the evidence that there was some order in the formation of the new orientation, the controlling factors must be examined. Each grain of every mineral present has one or more external and internal directions in which friction is at a minimum, and therefore failure is easiest. Some of the constituents, such as clay and calcite, are exceedingly fine-grained. The more resistant and less easily broken quartz particles are embedded in this fine matrix and are generally not in contact with one another. As force was applied, the fine-grained matrix, which presents many more directions of reduced friction because of the fineness of the grain and the nature of the material, may have begun to move in the directions in which motion was possible. The motion of the matrix would induce mechanical rotation on the quartz grains. These grains would be mechanically moved until they reached some position at which friction is at a minimum for the momentary strength of the deforming force.

The question now arises as to whether each grain reached this position individually and, consequently, whether failure was smoothly progressive or whether groups tended to reach this position simultaneously. The latter alternative would imply breaks in the continuity of the process of failure. In terms of the strain ellipsoid, which is used here only as a means of visualization, on which a constant force is being applied, was there one set of shear planes which gradually swept from their original positions to a position where relief might be had by translation, or was there a strain ellipsoid for each group of quartz grains arriving at the position of least friction? If the quartz grains arrived at their positions of least friction individually, failure would be taking place constantly, and the resulting diagram should show an even distribution of grains, some of which might have been rotated after failure. Instead, each diagram shows several fairly well-defined maxima in the girdle, as though the process had taken place under a constant force, and failure had taken place at intervals as each group reached the position of minimum friction.

These groups may have reached this position by the method out-

lined above. An alternative method of group failure, however, requires less rotation of individual grains and is brought about by the building-up of sufficient stress so that the grains in the most favorable position will fail. This gives one set of maxima. After relief the force builds up again until another set of grains, which have reached the most favorable position, fail and form another set of maxima. Either method would move grains from their original orientation and should form girdles with maxima. In order to understand this process in the rock, it is necessary to visualize one strain ellipsoid for the set of maxima forming at a given instant. At the same instant there may be a different ellipsoid for each individual grain in the rock depending on the reaction of that grain to the deforming force.

Therefore, it appears that the formation of the new fabric presented by the quartz in the mudrock was facilitated by the presence of a very fine-grained matrix of calcite and clay, in which the quartz grains were relatively free to move. Relative grain size controlled the rate and amount of rotation, since a space occupied by fine grains presents many more opportunities for preferred directional failure than an equal space occupied by larger grains. The separation of larger grains from one another by more than one diameter, especially in a medium having more directions of failure than the grains themselves, gives the larger grains opportunity to simulate the failure of the finer material by rotation to preferred positions.

In the sandy mudrock and in the mudrock it was seen that the component parts of the rock had moved relative to one another at progressively different velocities according to immediate mineralogical environment. For the rock this was shear; for the quartz, rotation and translation. The chief difference between the two lay in the maximum size of the particles and the relative spacing of the zones of movement. Megascopically, the sandy mudrock as well as the mudrock could be said to have fracture cleavage, although the cleavage of the mudrock is much more closely spaced. If the relative grain size of matrix and quartz grains remained constant and the maximum grain size was reduced to almost submicroscopic proportions, megascopically the cleavage would resemble flow cleavage.[7]

[7] This similarity will continue until the development of an abundance of new mica confines further failure to parallel surfaces. In the present incipient stage the micaceous

Assuming the process to be essentially the same, i.e., shear between component parts of the rock in zones the width of which depends on the grain size of the matrix and larger grains and translation and rotation of the more durable grains, the chief difference between fracture and flow cleavage in sediments in incipient metamorphism is one of spacing of shears dependent on the maximum size of grains included in the matrix.

The cleavage in the Moccasin occurs only in the beds in which there is a peculiar lack of sorting such that strong grains of quartz of widely different sizes are surrounded by weaker grains of calcite and micaceous clay. Where there is an abundance of clay and very little calcite, shear zones can easily develop. It is this characteristic which has rendered some of the beds of the Moccasin relatively incompetent, by comparison with other fine-grained argillaceous sediments in the same section, and which accounts for the widespread development of its cleavage.

ACKNOWLEDGMENTS.—The writer wishes to express his most sincere gratitude to Professors C. M. Nevin and J. D. Burfoot for their guidance and criticism during his study of the Sander method and its application to the present problem while he held the Eleanor Tatum Long Fellowship in Structural Geology at Cornell University. As an advanced fellow of the Belgian American Educational Foundation, Inc., it was possible to complete the analyses and to visit the laboratory of Professor Bruno Sander at Innsbruck, Austria. The writer is greatly indebted to Professor Sander for reading a preliminary draft of this manuscript, to which many changes and additions have since been made, and for the liberal giving of his time.

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clay flakes are too small to exert directional control. Calcite with its three, and multiples of three, sets of parallel planes, and quartz, with its rigidity, are the present controlling factors. Differential spacing of, and deviation from, the shear surfaces are the result of this control.

FROZEN GROUND IN SIBERIA[1]

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ABSTRACT

Permanently frozen ground underlies 3,728,900 square miles of Soviet territory, largely in eastern Siberia. Ice is not always present, but temperatures remain below 0° C. to depths down to 890 feet. In some places unfrozen layers are found between frozen ground. Most frozen ground has acquired its low temperature from the atmosphere.

DISTRIBUTION AND RESEARCH HISTORY

Three and three-quarter million square miles of Soviet territory are underlain by permanently frozen ground. During the brief summer the surface soil thaws for a few feet down, but under this the temperature remains below freezing to depths of hundreds of feet. Ice is not always present, nor is the phenomenon restricted to loose soil; all types of material are involved, including bedrock. The essential characteristic of permanently frozen ground is a temperature below 0° C. which persists through at least one summer. In contrast, seasonal freezing is restricted to the zone where summer thaw dissipates winter cold.

When examined in detail, the phenomenon of frozen ground presents many irregular situations. Alternate zones of frozen and unfrozen ground may be found one below the other, some of them dry, others with water or ice. In some Arctic areas—for example, Khatanga—frozen ground is found beneath the sea. Unfrozen localities are surrounded by frozen areas, and the reverse. While frozen ground is increasing in depth or area in certain localities, it is degrading in others. In some areas, where frozen ground did not formerly exist,

[1] Based upon field studies in Igarka (67° N. Lat.), on the Yenesei River, and on Russian literature, especially M. I. Soumgin, *Permanently Frozen Soil in the Limits of the U.S.S.R.* (Moscow: Academy of Sciences of the U.S.S.R., [1937]), pp. 379 (in Russian), and N. A. Tsitovitch and M. I. Soumgin, *Principles of Mechanics of Frozen Grounds* (Moscow: Academy of Sciences of the U.S.S.R. Press, [1937]), pp. 432 (in Russian). See also Constantin Nikiforoff, "The Perpetually Frozen Subsoil of Siberia," *Soil Science*, Vol. XXVI (1928), pp. 61–67.

the soil is known to have become frozen for a few years; that is, winter freezing remains in the ground during the following summer.

Permanently frozen ground has been recognized since the seventeenth century and has been studied in 404 localities, chiefly in northern and eastern Siberia. The principal localities are shown in Figure 1. Detailed examination dates from the digging of a well in Yakutsk in 1827 and its study by Middendorf. The eighteenth century may be termed the "academic period" of study, with interest in extent and depth. With the building of the Trans-Siberian Railway late in the nineteenth century, the practical aspects of the problem began to be appreciated, for bridges and other structures founded on ice presented new engineering difficulties. The clearing of the forest for these construction purposes allowed melting in the upper part of the frozen zone, so that the roadbed settled into thawed soil. Within the past decade Soviet scientists have given detailed and systematic attention to the scientific aspects of negative soil temperatures. Numerous experimental stations have been established and are producing an extensive literature, including a serial publication on frozen ground.[2] The digging of shafts in frozen ground is somewhat similar to normal rock excavation; but whenever temperatures rise above freezing, instabilities develop. Current research has had to solve a number of complicated problems.

The extent of frozen ground in northern Siberia is shown in Figure 2. Scattered localities are present in the Kola Peninsula; but the region of continuous freezing lies east of the White Sea, along a line somewhat south of the Arctic Circle and extends as far as the Yenesei Valley. Near latitude 65° N. the southern limit of permanent freezing crosses the river and swings southward near the eastern side of the Yenesei into Mongolia, where its exact course is unknown. Only small parts of the Amur basin and southern Kamchatka lie outside the frozen area. Thus, almost the entire eastern half of Siberia has underground temperatures below 0° C. throughout the year. The Arctic islands north of the mainland also have permanently frozen subsoil. Outlying frozen areas are present in the

[2] Published by the Moscow Academy of Science, Commission for the Study of Frozen Ground (five bulletins to 1937).

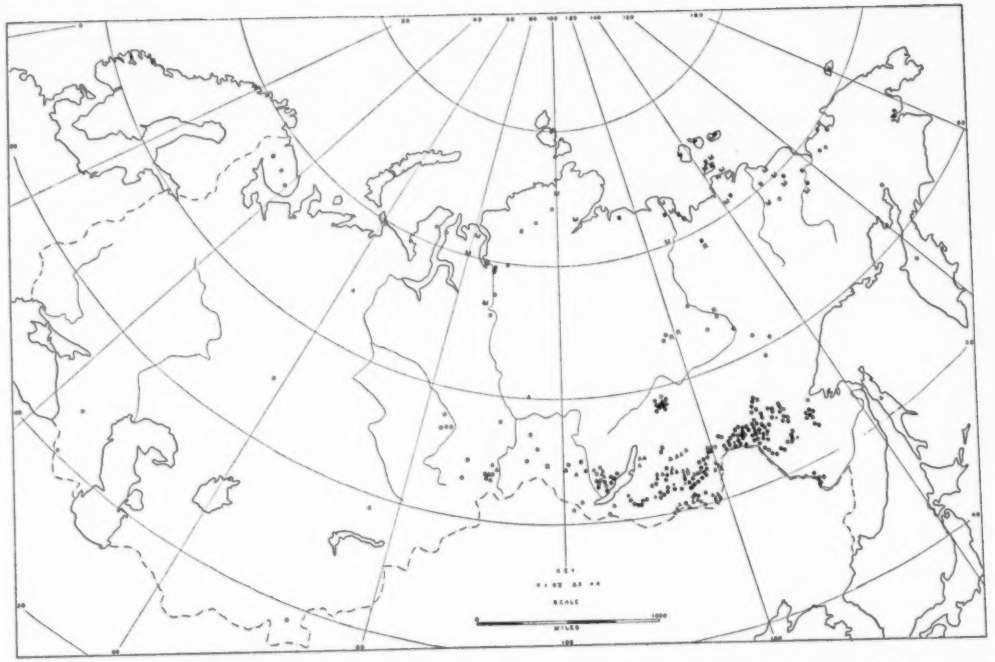

FIG. 1.—Frozen ground studied in 404 localities. Key: *1*, proven frozen ground; *2*, usual indications of the presence of frozen ground; *3*, studies of depth of summer thaw; *4*, alternate horizons of frozen and unfrozen ground; *M*, fossil mammoths; *R*, fossil rhinoceros. Frozen ground with evidence of considerable ice is shown by black squares.

mammoths; *R*, fossil rhinoceros. Frozen ground with

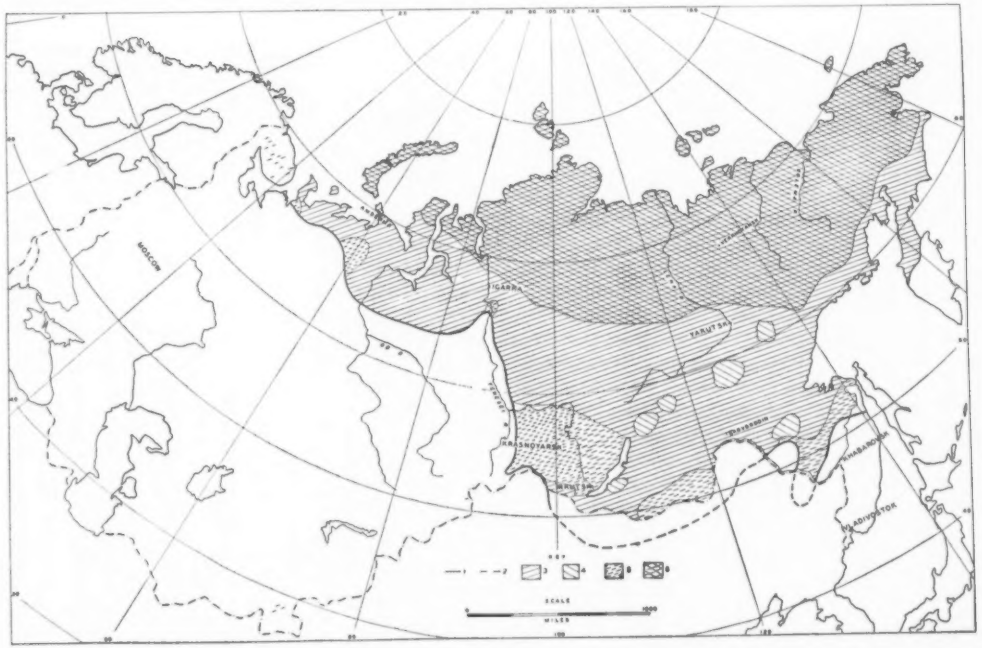

FIG. 2.—Distribution of permanently frozen ground. Key: *1*, southern boundary of permanently frozen ground within the U.S.S.R.; *2*, probable limits of permanently frozen ground outside U.S.R.R.; *3*, research data lacking on character and extent of frozen ground, islands of thawing probably rare in north, but increasingly present to the south; *4*, local islands of thawed ground known to be present; *5*, local islands of permanent freezing surrounded by unfrozen areas; *6*, area of uninterrupted frozen ground.

Caucasus, Pamirs, Urals, and upper Ob Valley. Even parts of Moscow have soil temperatures at a depth of 5 meters as low as 0°.1 C.

The total area involved is 9,657,960 square kilometers, or 3,728,900 square miles. This is 47 per cent of the entire U.S.S.R, or more than the area of the United States.

TYPES AND DEPTHS

As may be seen in Figure 1, several situations prevail as to the local continuity of freezing. The distribution of these types roughly corresponds to present temperature conditions at a depth of 10–15 meters in the permanently frozen ground. In the northern areas of ever frozen ground, temperatures at this depth are below −5° C. In the southern areas, where islands of frozen ground are surrounded by unfrozen ground, temperatures at a depth of 10–15 meters within the frozen ground do not go below −1°.5 C.

Several types of frozen ground exist. Usually it is rock or soil with normal amounts of water. Masses of pure ice, however, are found in situations which suggest that they were lakes or rivers which froze and became covered with debris. Some of these are 100 square kilometers in extent and as much as 80 meters thick. Elsewhere masses of ice exist beneath the sea—records, perhaps, of a time when the entire body of water was frozen. Masses of stony ice exist, probably remnants of Pleistocene glaciers. Still other accumulations of ice may have developed where rising ground water met subfreezing ground temperatures. Especially cold winters may produce, outside the normal area, frozen ground that will survive for a summer or so.

The first studies of the lower limit of freezing were made at Yakutsk in 1827, when the Shergeen shaft was dug for water (Fig. 3). Although digging was continued intermittently for a decade and extended to a depth of 117 meters, unfrozen ground was not reached. Ground temperatures in winter range from −21° C. near the surface to −6°.52 C., at a depth of 30.48 meters. While summer does not melt this upper zone, it causes the temperature to fluctuate. Below this depth the temperature increases regularly without regard to seasons, reading −2°.4 C. at 117 meters. The shaft has since been deepened, and frozen ground is known to extend to 145 meters.

At Igarka the lower limit of frozen ground is 57.5 meters; along

the Kolema River drill holes reach 113 meters, with no bottom found; in Trans-Baikalia a shaft has been put down 70.4 meters without reaching the base; another along the Amur goes to 74 meters

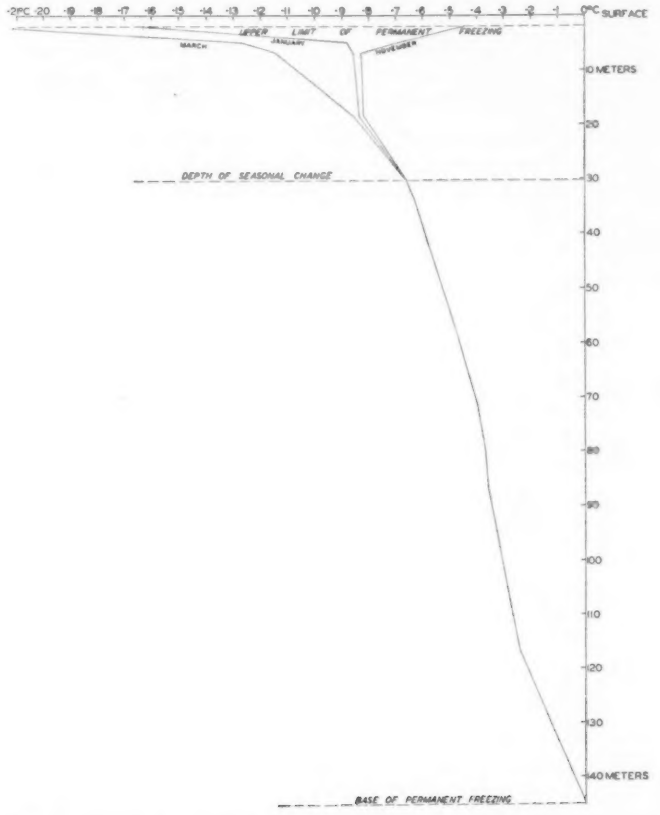

FIG. 3.—Temperature profile of the Shergeen Shaft at Yakutsk. Below the zone of seasonal change, extending to 30 meters, temperatures increase steadily until unfrozen ground is reached at 145 meters.

and is still in frozen ground The greatest depth known is at Amderma, 69°50′ N., 62° E., where the lower surface of the permanently frozen zone is 274 meters (890 feet) deep.

Apparently the lower surface of permanent subfreezing temperatures is uneven, for in many localities near-by drill holes show considerable variation. This condition is probably due to ground water circulation and to the changing conductivity of the rock. Depth of

TABLE 1

DEPTH OF FROZEN GROUND*

Place of Observation	Depths in Meters	Notes	North Latitude	East Longitude
I. North European part:				
1. Pustozersk	17.83	.....	67°	53°
2. Talba Mine	23.25	.....	.....	.....
3. Vorkut Mine	69.26	No bottom	.....	.....
II. Arctic fringe:				
1. Amderma	274	No bottom	69°50′	62°
2. Igarka	57.50	.....	86°68′	.....
3. Ust Anadir	100	No bottom	64°25′	177°
4. Ust Yenesei Port	100	No bottom	69°38′	84°22′
III. Yakutia:				
1. Kolyma River at Ust Utena	113	No bottom	63°	151°
2. Uspenski Mine	50–51	.....	.....	.....
3. Yakutsk	145	.....	61°58′	129°44′
IV. Area west of Baikal:				
1. Aliberov Mine	100	No bottom	.....	.....
2. Perecelensk Height	30	.....	53°17′	105°28′
3. Taishet	1–5	.....	56°	97°
V. Trans-Baikal:				
1. Busheley	70.40	No bottom	52°48′	117°35′
2. Petrovsk	40	.....	.....	.....
VI. Far Eastern area:				
1. Central Zeya	50	No bottom	54°	127°
2. Skovorodin (Rukhlovo)	40	.....	53°58′	123°57′
3. Taldan	70–71	.....	54°	126°

* Soumgin, *op. cit.*, pp. 94–95.

freezing is not merely a function of atmospheric temperature but is opposed by the internal heat of the earth.

The temperature regime of the upper zones is closely correlated with seasonal air temperatures, snow cover, forest and moss insulation, ground moisture, soil characteristics, and exposure to the sun. As a regional generalization the deepest freezing appears to be related to the greatest present annual temperature range. Where the

average annual air temperatures are from 1° C. to 2° C., frozen ground typically extends to a depth of 20 meters; where air temperatures are 0° C. to 1° C., the depth is as much as 50 meters; where air temperatures are below freezing, frozen ground extends to over 80 meters. Thus, 1° of temperature change involves a depth of 30 meters. Where there is a spongy layer of moss 1 or 2 feet thick, as in the tundra, summer thawing may extend less than a foot into the mineral soil. Likewise, a protective layer of snow will prevent extremely low winter temperatures from penetrating into the earth. Marked differences are found in the depth of summer thaw between southward-facing slopes and those which receive less of the sun's warmth.

Studies at Bomnyak in Amur Oblast from 1911 to 1913, when the average yearly air temperature was −4°.7 C., have shown that a snow cover in December and January of 30 centimeters is sufficient to prevent additional freezing and permit the warming of the surface layers from below; whereas during 1917–19, with a yearly temperature of −5°.2 C. and a snow cover of but 10 centimeters, winter cold penetrated the ground, so that its mean temperature was reduced.

Probing along the sandy banks of the Yenesei at Dudinka, latitude 69° N., showed frozen ground at a uniform depth of 4 feet below water-level in September, 1937.

Whenever there is a moderation in temperature or where the natural vegetation has been cleared, as for a settlement, road, or cultivated field, the upper limit of permanent freezing is lowered several feet. Winter freezing may not penetrate to this depth, so that a constantly unfrozen horizon is created. The depth to permanently frozen ground in Igarka ranges from 1 to 10 meters and more; and below small lakes, borings to 30 meters encountered no frozen ground at all. Under cultivated fields at the experimental farm, summer thaw normally extends 15–18 feet in sandy soil. One or more permanently unfrozen zones underlie considerable parts of the Igarka area (Fig. 6).

Studies over a period of years around the periphery of the frozen region suggest that the upper surface of permanent freezing is being lowered, but whether this is due to artificial causes or to cyclic climatic change is uncertain. It is possible that degradation may be

taking place in the bottom surface also, owing to warmth from the interior of the earth. Waves of cold sent into the ground during succeeding centuries may be of different intensity, so that there will be corresponding differences as to the depth to which the 0° C. isotherm will penetrate.

As an example of deeply buried frozen ground, Nikiforoff states: "A frozen layer, almost 70 feet thick, was found near Petrovsky Zavod in the Trans-Baikal province (51°17′ N. latitude), with its upper surface at a depth of approximately 103 feet."[3]

TABLE 2*

AMUR PROVINCE, AT 54°22′ N. LAT., 122°54′ E. LONG.

Layers	Depth in Meters
Unfrozen†	0.00– 9.39
Frozen	9.39–13.12
Unfrozen†	13.12–16.07
Frozen	16.07–16.45
Unfrozen†	16.45–20.48
Frozen	20.48–21.12
Unfrozen†	21.12–28.42
Frozen	28.42–31.17
Unfrozen†	31.17–33.08
Frozen	33.08–50.24

* Soumgin, *op. cit.*, p. 74.

† Some of the unfrozen layers contain artesian water.

PLEISTOCENE GLACIATION IN SIBERIA

The extent of Pleistocene glaciation in Asia is gradually becoming known (Fig. 4). Across western Siberia ice descended to latitude 59° N. along the Irtysh, 60° N. on the Ob, and 61° N. at the crossing of the Yenesei. East of the Yenesei, ice was confined to considerably higher latitudes; and the boundary reaches the Arctic coast at longitude 115° E. Apparently, most of the Lena basin was unglaciated. The highlands northeast of Lake Baikal and east of longitude 125° E. were ice covered, but it is not certain that there was a continuous ice sheet. Much of Siberia is cold enough for a continental glacier even today but has a scanty snowfall. This was also presumably the case throughout the Pleistocene.

The area of permanently frozen ground does not correspond to the glaciated area. Where the ice moved farthest south, in western Siberia, the limits of frozen ground are far to the north, in the tundra.

[3] *Op. cit.*, p. 65.

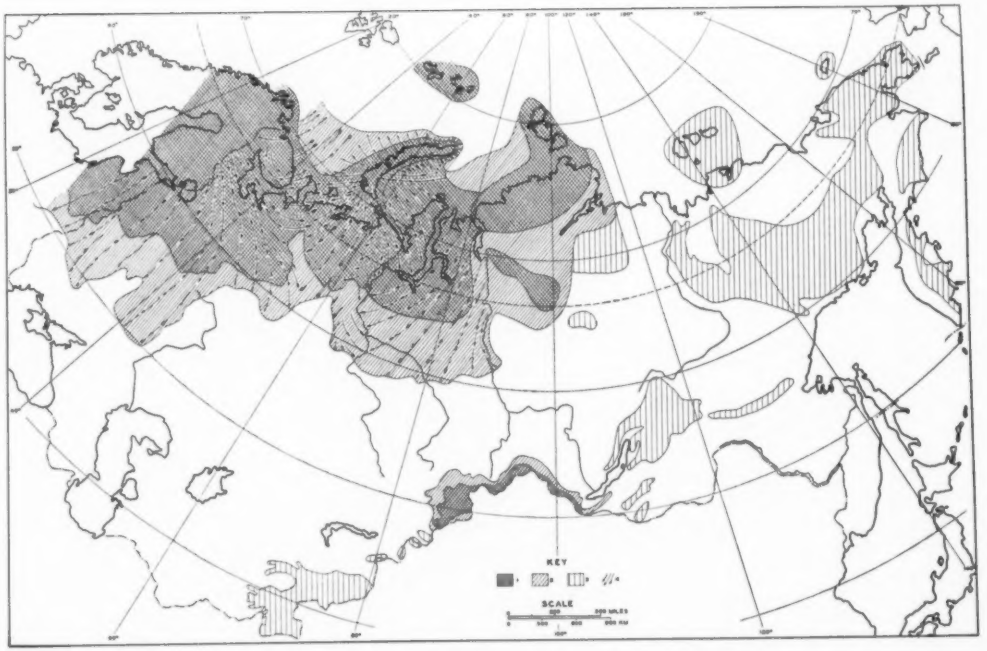

FIG. 4.—Glaciation in the Soviet Union. Key: *1*, area covered by last ice sheet, approximately Wurm.; *2*, maximum extent of known glaciation, approximately Riss.; *3*, regions of Quaternary glaciation for which exact knowledge is not available; *4*, probable direction of ice movement.

In the regions east of the Yenesei River, where the ice was absent, frozen ground extends south into Mongolia. Ice is a poor conductor, and the thick glacial blanket must have insulated the earth from abnormally low atmospheric temperatures. Whatever the origin of Siberia's frozen ground, ice sheets were not the cause, with the possible exception of local masses of still-buried Pleistocene ice.

PRESENT CLIMATIC CONDITIONS

Siberia is cold. The annual isotherm of 0° C. covers almost all the eastern part of the country, reaching south to Manchuria. In the vicinity of Verkhoyansk the yearly average is −15° C., and at Yakutsk it is −10° C. Winters everywhere exceed summers in duration and intensity. At Dudinka temperatures drop below freezing at the end of September and remain below until mid-May. At Oimekon, southeast of Verkhoyansk, an absolute minimum temperature of −78° C. (−104° F.) has been recorded. Rivers and lakes freeze to a thickness of several feet. North of the Arctic Circle, river and lake ice forms from 40 to 80 inches; to the south the thickness commonly exceeds 30 inches. The northern third of Siberia has 200 days a year with a temperature below −5° C. and only 100 days with temperatures over 5° C. All the permanently frozen area has at least 180 days below 0° C., and almost nowhere in this area does the temperature rise to 20° C. for more than two weeks.

The precipitation throughout eastern Siberia is light except in Kamchatka and the lower Amur Valley. Total summer precipitation in the Lena basin averages 8 inches, and the winter precipitation amounts to but 2 inches. Snow cover is thin in most of the permanently frozen area. The Yenesei Valley commonly receives a total of 32 inches of snow during the winter; the Lena, 16 inches; and the Trans-Baikal area, only 8 inches.

The distribution of thin snow cover thus shows a correlation with frozen ground. Presumably, the general relationship between the dry eastern and more humid western half of Siberia also prevailed in glacial times. The area of frozen ground roughly corresponds to the present distribution of subfreezing isotherms.

Critical evidence as to the amelioration of temperature within present decades is not available, although there is a tendency to believe that moderation is in process. In some peripheral areas where

frozen ground was present a century ago, it has now disappeared. This has taken place in regions where, for agricultural purposes, the forest has been cleared and the moss removed, so that the influence of climate is uncertain.

CAUSES OF FROZEN GROUND

Wherever the average annual air temperature is below freezing, an increment of cold is added to the ground each winter which is not dissipated by summer heat. Thus, successive annual "waves of cold" are sent into the earth; expressed otherwise, heat losses by radiation exceed the summer gain from insolation. The lower the annual temperature, the colder and more penetrating the wave. Factors of soil cover, exposure, ground water, and the conductive quality of the earth may accelerate or retard the process but do not entirely stop it. As these waves of cold descend, they encounter the warmth of the earth's interior, so that the depth to which the isotherm of 0° C. penetrates is a contest among several factors. Decades of unusually severe air temperatures will push the base of the frozen ground deeper, whereas periods of relative warmth will enable internal heat to thaw the bottom surface. Temperature readings in some drill holes show colder zones between warmer zones, apparently the relic of cyclic atmospheric conditions. Because of the poor conductivity of rock, it may require centuries for increments of cold to reach the base of the frozen ground.

In the study of contemporaneous air temperatures in the area of permanent freezing, Grigorieff has prepared a freezing formula, in which the depth of frozen ground is directly proportional to the temperature and duration of the winter months and inversely proportional to the total snow cover, the temperature and duration of summer months, and the amount of precipitation in the period with positive temperatures.[4] The equation is as follows:

$$\text{Coefficient of freezing} = \frac{\text{Sum of the monthly negative temperatures}}{\text{Average monthly thickness of snow cover in centimeters} \times \text{Sum of monthly positive temperatures} \times \text{Sum of average rainfall in millimeters during months with positive temperatures}}$$

[4] Soumgin, *op. cit.*, p. 219.

Soviet scientists generally agree that permanently frozen ground is the result of low air temperatures, but there is no agreement as to whether the freezing is the result of present (i.e., postglacial) climates or whether it is older.

Prior to the present century, frozen ground was thought to be of great antiquity—an inheritance from the Ice Age. Today there is an increasing tendency to recognize that frozen ground may develop under existing climatic conditions. While this may be partly true, the phenomenon is very complex, and there is no uniform relationship between present climate and subsurface temperatures. Soumgin and other Soviet scholars thus tend to favor an ancient geological origin. The great depth involved, the large masses of buried ice, the presence of frozen mammoths, and the apparent current tendency toward degradation—all point to an ancient origin.

Neolithic remains have been found in Mongolia, and mammoths are present in the frozen ground of the north. The former points to the recency of the freezing and suggests that the process is still in operation, whereas mammoths are considered to be preglacial, although specific dating is impossible. The existence of permanently unfrozen zones between the top of permanently frozen ground and the bottom of winter freezing, as at Igarka and elsewhere around the periphery of the area, indicates that degradation is in process. Thus, the annual wave or increment of temperature now conducted into the earth appears to be above freezing. In certain shafts, too, the lower depths are colder than the surface. This favors an ancient origin under more severe climates, probably during glacial times in unglaciated areas or in glaciated areas just after and before the ice cover.

Wherever current atmospheric conditions are more mild than those at the time of maximum development, neither upper nor lower limits of frozen ground are maintained. At Skovorodin on the Trans-Siberian Railway (53°58′ E., 123°57′ N.) temperatures decrease from −0°.5 C. near the surface down to −1°.5 C. at 28 meters, and then rise to freezing at 50 meters (Fig. 5). At this station seasonal changes extend to a depth of 14 meters. The change in temperature gradient indicates wastage due to the failure of present air temperatures to supply as much cold as at the time of maximum development.

While it is clear that existing climates in northeastern Siberia are competent to produce frozen ground, there is no indication as to how long may be required to develop subfreezing temperatures to depths of several hundred feet. The limited period of postglacial time scarcely seems adequate. Permanent freezing may well have originated in early Pleistocene or even Pliocene time under climatic conditions more or less comparable to the present and may have persisted through the ice interval to today. The practical problem is not so much the time of original freezing as the present conditions in which it can be maintained. As Grigorieff has pointed out, "if permanent freezing originated in the past geologic age, then it maintains itself only in those areas where it could develop now, because, otherwise, it would have disappeared long ago."[5] In the north, where annual air temperatures near the mouth of the Lena, at Sagastir, are now as low as −17° C. and the snow cover slight, additional freezing is in progress. Near Lake Baikal, where the yearly temperature averages 0° C., frozen ground cannot hold its own, and degradation is going on.

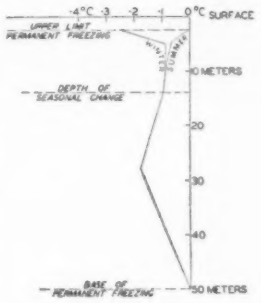

FIG. 5.—Temperature profile at Skovorodin. The irregular temperature gradient below 14 meters suggests a former period of colder climate.

IGARKA

Igarka is the port of the Yenesei, although 400 miles from the sea; and a new city of 15,000 people has developed in connection with lumber export.

At Igarka is located an experimental station for frozen ground which is making detailed studies. Numerous drill holes have been put down, loading tests are being made for foundations, and three shafts have been sunk to depths of 5, 7.2, and 9 meters. These shafts have horizontal drifts which permit an examination of the frozen ground. The material is silt and clay, coarsely varved. Logs up to a foot in diameter are present, with a few boulders. Clear transparent

[5] *Ibid.*

ice is present in horizontal lenses which make up from one-tenth to one-quarter of the total thickness. These lenses are from 1 to 4 inches thick and several feet long and are sometimes faulted a few inches. Electric lights enable one to see through the ice a foot or more, for it seldom shows crystalline structure. Air bubbles are present near the top of the lenses.

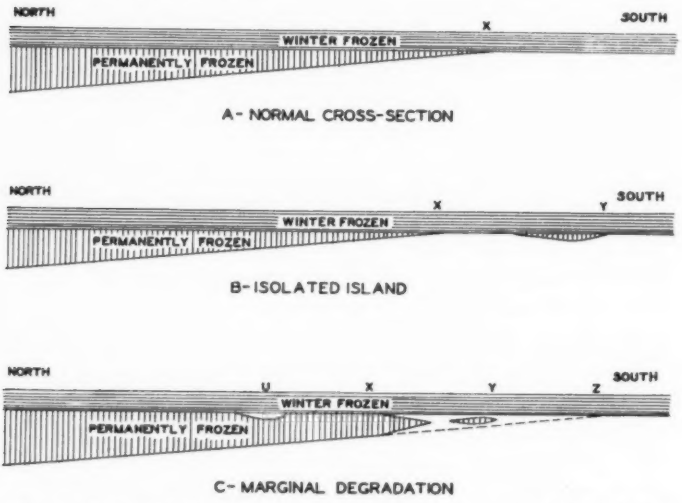

FIG. 6.—Diagrammatic cross section of frozen ground from north to south across Siberia, showing the thinning of permanent freezing southward and the conditions (*B* and *C*) where regional thawing has taken place. Key: *X*, southern limit of contact between permanently frozen zone and winter freezing; *Y*, southern limit of outlying areas of permanently frozen ground; *Z*, probable former extent of frozen ground; *U*, zone of unfrozen ground between base of winter freezing and top of permanently frozen ground.

A cross section of ground temperatures in winter at Igarka (Fig. 6) shows that there are horizons which never freeze. In some instances unfrozen zones are present between ground which is permanently frozen. Similar situations are reported elsewhere. Winter freezing penetrates several feet in some cases; elsewhere the cover of vegetation and snow and the character of the soil limit winter freezing to a few inches. Lakes which do not freeze to the bottom also protect the underlying ground.

The valley of the Yenesei in the vicinity of Igarka is a typical ground moraine surface with innumerable lakes and undrained depressions. Seen from the air, the surface appears to be a striking illustration of continental glaciation. Such it undoubtedly is, for morainal ridges and glaciated stones are abundant. However, the absence of frozen ground in drill holes beneath certain of these depressions and the extent of ice lenses shown in the Igarka shafts suggest that some of these apparent kettle holes may be the result of differential thawing of the ground. Where ice lenses constitute from one-tenth to one-quarter of a vertical section to a depth of a hundred feet, the melting of this ice would create well-developed kettle holes. The causes of such differential melting are unknown; they may possibly be due to vertical movements of ground water. The land is flat, so that artesian circulation is improbable, although present elsewhere beneath frozen ground.

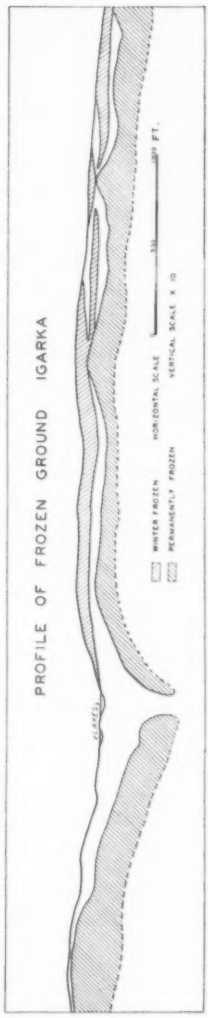

FIG. 7.—Cross section of frozen ground at Igarka. The scale is in feet, and the profile extends for about a mile. One or more zones of permanently unfrozen ground are typically present.

To the north of Igarka, especially near Dudinka, these irregular lakes cover as much as one-quarter of the surface, ranging in size from a few hundred feet to a mile in diameter. No subsurface studies have been made in this area, but the majority of the lakes appear to be normal kettle lakes.

The construction of a modern city, together with wharves and foundations for heavy machinery, above frozen subsoil presents serious foundation problems. Piling for wharves is in some cases driven

into unfrozen ground along the river; elsewhere steam jets thaw the soil as the pile is sunk. Foundations for the engines in the lumber mill had to be sunk 22 meters to bedrock. Perhaps the most striking aspect of frozen ground is the problem of water mains. Whenever possible, these are laid in unfrozen horizons; elsewhere, the trench is lined with boards and filled with moss or sawdust, and alongside the 8-inch main is placed a steampipe to keep it from freezing.

House construction must provide insulation not only in the walls but under the floors. The first houses, with log floors laid directly on the ground, settled during the winter as the heat from the large brick stoves thawed the ground. Present construction methods call for 2 feet of moss or sawdust on the ground, then 6 inches to 1 foot of air space, then a thick floor, above this 6–8 inches of earth, and finally the floor proper. Around the sides of all buildings, reaching up some 3 feet, is an outer wall, enclosing a foot of insulating material.

Igarka has one of the northernmost farms in Asia, with 500 acres under cultivation. Before clearing the natural vegetation, permanently frozen ground lay 1–1½ meters below the surface; since cultivation on sandy soil, the depth has been increased to 5 or 6 meters One well, with a depth of 20 meters in an unfrozen pocket, yields 800 buckets of water daily throughout the year; another near-by well freezes during the winter. More than a million rubles worth of farm products were obtained in 1936, including vegetables, root crops, and milk from 400 cows.

Weather records from 1930 to 1937 show the variability of Arctic climate, for during these years the frost-free period has varied from 75 to as long as 128 days. With this variability no safe conclusions can yet be drawn as to current climatic trends or changes in frozen ground.

A PETROGRAPHIC STUDY OF THE NIAGARAN ROCKS OF SOUTHWESTERN OHIO AND SOUTHEASTERN INDIANA

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ABSTRACT

The Niagaran rocks of southwestern Ohio and southeastern Indiana exhibit several lithologic and paleontologic facies on their respective flanks of the Cincinnati Arch. Detailed stratigraphic zoning of these rocks, subsequent laboratory investigation of thin sections, insoluble residues, and rock powders, and chemical analyses of the samples collected show (1) the lower part of the Dayton limestone of Ohio is equivalent to the entire Dayton limestone of Indiana; (2) the Osgood shale of Ohio is equivalent to the upper Osgood shale of Indiana; (3) a portion of the Laurel limestone of Indiana is equivalent to the entire Laurel limestone of Ohio; (4) the Euphemia, Springfield, and Cedarville dolomites are true dolomites, whereas the Dayton and Laurel limestones are dolomitic limestones; and (5) the water in which the Niagaran sediments were deposited appears to have varied in depth between 150 and 500 feet.

INTRODUCTION

The Niagaran rocks under consideration extend as a narrow belt northward from Louisville, Kentucky, to Rush County, Indiana, and from the Indiana line, near Richmond, eastward to Cedarville, Ohio (Fig. 1). Foerste[2] classified these rocks as shown in Table 1.

TABLE 1

Southeastern Indiana	Southwestern Ohio
	Cedarville dolomite
	Springfield dolomite
	Euphemia dolomite
	Massie shale
Laurel limestone	Laurel limestone
Osgood formation	Osgood shale
Basal Osgood limestone	Dayton limestone
(Dayton limestone)	

However, since this and other classifications were chiefly based on lithology, these rocks appeared to provide an excellent test of the

[1] Kingwood Oil Co., Effingham, Ill.

[2] A. F. Foerste, "The Silurian Fauna," *The Paleontology of Kentucky: A Symposium* ("Kentucky Geological Survey Series 6," Vol. XXXVI, 1931), p. 173.

FIG. 1.—Areal geology of southeastern Indiana and southwestern Ohio

applicability of petrographic methods in establishing actual stratigraphic and paleogeographical relationships.

METHODS

In sampling, units of less than 5 feet in thickness were generally considered as a single lithologic zone, and in such cases but one sample was collected. Thicker units were zoned, and a sample collected from each zone, the zones being established by observing the color of the fresh rock, its color on weathering, its crystallinity, texture, relative hardness, and bedding. The samples taken represent the following lithologic zones in Indiana and Ohio (Figs. 2 and 3) as determined in the vicinity of Charlestown, Madison, Butlerville, Greensburg, and Andersonville, Indiana, and in the vicinity of New Paris, Lewisburg, Covington, Springfield, and Yellow Springs, Ohio (Fig. 1). The thicknesses stated show the variations in thickness of each zone or unit (Table 2).

Ninety-nine thin sections and an equal number of insoluble residues were made from representative specimens of the samples collected. The thin sections were cut at right angles to the bedding of the rock. Impregnation of all specimens with bakelite was necessary to prevent disintegration of the thin sections during grinding. Approximately 100 gm. of rock were digested in 10 per cent hydrochloric acid, the fragments used measuring 3.962–7.925 mm. across. All the insoluble residue except the finest material was washed and retained for examination.

Rock powders of the Dayton and Laurel limestones and the Euphemia, Springfield, and Cedarville dolomites of Ohio, fragments from 0.495–0.991 mm. across, were treated by the ferric chloride and ammonium polysulphide methods to determine the relative amounts of calcite and dolomite present. A number of chemical analyses of samples collected from the Dayton, Laurel, Euphemia, Springfield, and Cedarville units, made available through the courtesy of Dr. Wilber Stout, state geologist of Ohio, were very helpful aids.

Microscopic examination involved study of thin sections, insoluble residues, and powdered material. Thin sections were studied in the usual manner, minerals, textures, and unusual features being re-

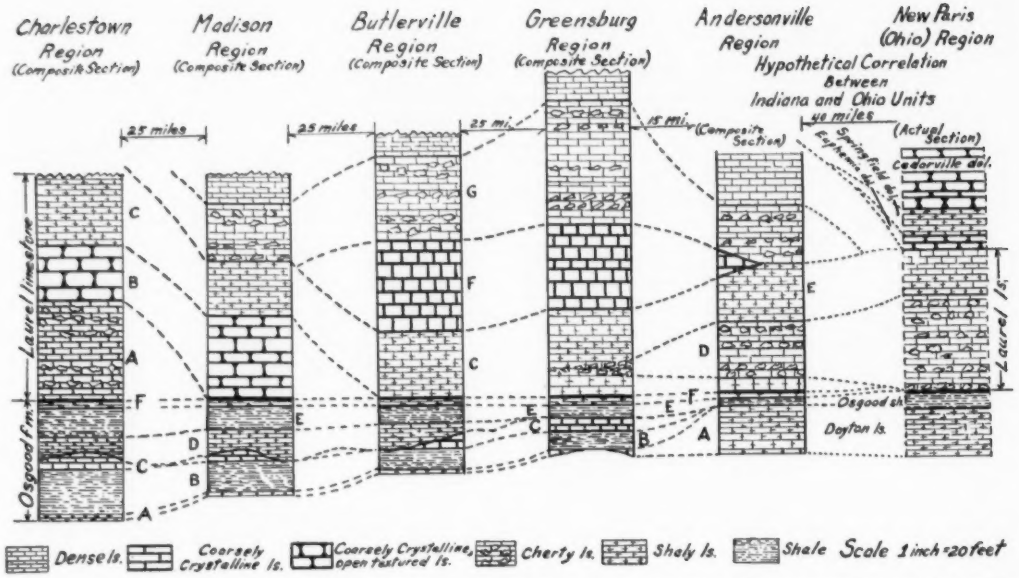

FIG. 2.—Columnar sections of the Osgood and Laurel units in Indiana, showing their lithologic character and their hypothetical correlation with Ohio Niagaran units.

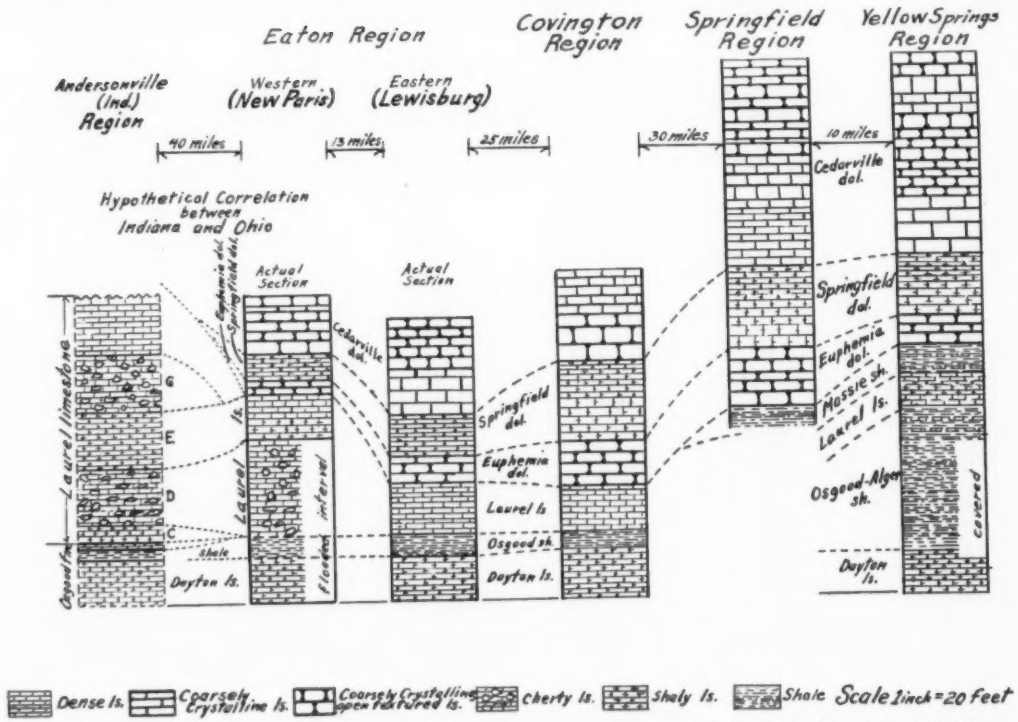

FIG. 3.—Columnar sections of the Niagaran units of southwestern Ohio, showing their lithologic character and their hypothetical correlation with Indiana.

corded. Insoluble residues and powders were examined under a binocular microscope. Dark residues were sprinkled on white cards and light residues on black cards.

TABLE 2

LITHOLOGIC ZONES IN INDIANA

	Thickness in Feet
Laurel limestone	
Zone *G*, dense, cherty limestone	4–10
Zone *F*, coarsely crystalline limestone	0–16
Zone *E*, dense, rather shaly limestone	10
Zone *D*, dense, cherty limestone	0–8
Zone *C*, dense, rather shaly limestone	3–15
Zone *B*, coarsely crystalline, vuggy limestone	9–15
Zone *A*, dense, shaly limestone	0–18
Osgood formation	
Zone *F*, upper, shaly limestone	1–2
Zone *E*, upper shale	1–5
Zone *D*, middle, shaly limestone	0–5
Zone *C*, middle, coarsely crystalline limestone	0–3
Zone *B*, lower shale	0–8
Zone *A*, lower shaly limestone (Dayton)	0–8

LITHOLOGIC ZONES IN OHIO

Cedarville dolomite	
Upper, coarsely crystalline, vuggy dolomite	10–45
Lower, coarsely crystalline, vuggy dolomite	10–15
Springfield dolomite	
Upper, finely crystalline, vuggy dolomite	4–8
Lower, finely crystalline, vuggy dolomite	2–8
Euphemia dolomite, coarsely crystalline, vuggy	3–11
Massie shale	5–6
Laurel limestone, dense, rather shaly	5–8
Osgood shale	3–25
Dayton limestone	
Upper, dense, shaly limestone	4–5
Lower, dense, shaly limestone	4–5

OBSERVATIONS

Eighteen minerals were noted in the Niagaran units. These belong in two groups, detrital and authigenic, the latter group containing all but four of the minerals. The chief detrital mineral is quartz,

occurring as rounded grains from 0.015 to 0.4 mm. in diameter. It was found in nearly every unit in amounts up to 2 per cent of the residues. Other detrital minerals are sericite, hornblende, and garnet, the sericite occurring in shales, the hornblende and garnet in the Osgood and Laurel units at the eastern end of the outcrop in Ohio. The most abundant authigenic minerals are calcite and dolomite, composing from 30 to 98 per cent of the more calcareous units. Argillaceous material and chert are next in abundance, constituting 30 per cent of the shales and cherty limestones, respectively. Botryoidal chalcedony, quartz crystals, castic[3] silica, pyrite, marcasite, limonite, and gypsum are rarely present in excess of 1 or 2 per cent of any one unit. Sulphur, barite, and fluorite occur as mere traces.

Modes of occurrence and origin of minerals were disclosed by study of thin sections and insoluble residues. Pyrite, as cubes, cubo-octahedra, octahedra, and pyritohedra, are common in all types of rocks; but parallel growths of pyrite, replacing sponges, sponge spicules, and other organic structures, are limited to shales, shaly limestones, and coarsely crystalline limestones. Marcasite, in three forms—platy crystals, bladed crystals, and equidimensional, blocky crystals—occurs chiefly in shaly limestones. Glauconite, as dark-green pellets, dark-green fossil casts of gastropods, lighter-green castic material, light-green flaky fragments, and very light-green porous material, occurs chiefly in shaly limestones. In the porous form the mineral has filled the zoecial tubes and replaced the tube walls of bryozoa. Limonite, as limonitized pyrite or marcasite, or as castic material, is present in nearly all the units. Gypsum, as a result of concentration by groundwater, occurs as satin spar in vugs of dolomites and as selenite in limestones.

Chemical analyses confirmed the presence of limonite, barite, celestite, gypsum, and glauconite. The glauconite was identified by separate analysis, but its presence was suggested by relatively high percentages of ferrous oxide, alumina, potash, and soda in the analyses of the Dayton and Laurel limestones; units which contain

[3] The adjective "castic" is used to describe any insoluble residue having the form of a crystal impressed upon it. Silica, glauconite, and limonite are the most common castic residues.

relatively large amounts of glauconite. Moreover, analyses indicate the presence of marcasite, pyrite, and argillaceous material, as well as large amounts of calcite and dolomite. Calculations from the analyses show that lime-magnesia ratios for the Euphemia, Springfield, and Cedarville dolomites are nearly 1.401, and that these units are, therefore, nearly true dolomites, whereas the lime-magnesia ratios for the Dayton and Laurel limestones are 2.099 and 1.787, respectively. Hence the latter formations are dolomitic limestones, containing 76.06 and 87.19 per cent of dolomite, respectively. How-

TABLE 3

OCCURRENCE OF SPECIES

Ammodiscus exsertus Cushman
- Dayton limestone of Indiana
- Lower Dayton limestone of Ohio
- Zone *E*, upper Osgood shale of Indiana

Ammodiscus incertus (d'Orbigny)
- Lower Dayton limestone of Ohio
- Zone *C*, coarsely crystalline Osgood limestone of Indiana
- Zone *D*, middle shaly Osgood limestone of Indiana
- Zone *E*, upper Osgood shale of Indiana
- Zone *A*, Laurel limestone of Indiana

Lituotuba exserta Moreman
- Dayton limestone of Indiana
- Lower Dayton limestone of Ohio
- Zone *D*, middle shaly Osgood limestone of Indiana
- Zone *E*, upper Osgood shale of Indiana

Sorosphaera sp. Moreman
- Osgood shale of Ohio
- Massie shale

Bathysiphon deminutionis Moreman
- Zone *F*, upper shaly Osgood limestone of Indiana

Bathysiphon curvis Moreman
- Upper Springfield dolomite

Thurammina phasela Moreman
- Zone *D*, shaly middle Osgood limestone of Indiana

Thurammina triangularis
- Zone *F*, upper shaly Osgood limestone of Indiana

Thurammina sp. Moreman
- Zone *B*, lower Osgood shale of Indiana

Psammonyx sp.
- Zone *E*, upper Osgood shale of Indiana

ever, powder and thin-section examinations indicate that only 20–30 per cent of the carbonate in the limestones is dolomite, consequently some of the magnesia must be present in some other form, possibly as nearly pure magnesium carbonate or incorporated in the calcite molecule.

Several types of micro-organisms were observed—chiefly in the shales and shaly limestones. Of these, siliceous sponge spicules and arenaceous foraminifera are most important.

The sponge spicules are of three types, the common dermal spicule, the flesh spicule, and a modification of the five-rayed dermal spicule, which is termed a sponge plate. In the latter type a weblike plate connects four rays which lie in a plane perpendicular to the fifth ray. The sponge spicules are found consistently in Zone *D* of the Osgood of Indiana; in Zones *A*, *C*, and *D* of the Laurel of Indiana; in the entire Laurel of Ohio; and locally in the Springfield and Cedarville dolomites.

The occurrence of the foraminifera is significant, since foraminifera are not known to have been described from the Niagaran units of Ohio and Indiana. Table 3 indicates the Niagaran horizons of southwestern Ohio and southeastern Indiana in which each species occurs.

DIAGNOSTIC CHARACTERISTICS OF THE NIAGARAN UNITS

Certain diagnostic characteristics of the Niagaran units of southwestern Ohio and southeastern Indiana have been disclosed by the foregoing observations. Table 4 shows only the more diagnostic characteristics of each zone or unit, the characteristics being listed in the order of their importance.

TABLE 4

DIAGNOSTIC CHARACTERISTICS

Dayton limestone of Indiana
1. Chainlike growths of pyritohedra of pyrite
2. Foraminifera
   a) *Lituotuba exserta*
   b) *Ammodiscus exsertus*
3. Glauconite
   a) Porous
   b) Pellets
4. Castic silica

TABLE 4—*Continued*

Lower Dayton limestone of Ohio
1. Foraminifera
   a) *Lituotuba exserta*
   b) *Ammodiscus exsertus*
   c) *Ammodiscus incertus*
2. Clear dolomite rhombs penetrating fossil fragments composed of calcite
3. Cubes and octahedra of pyrite
4. Grains of quartz sand
5. Glauconite
   a) Fossil casts
   b) Castic
   c) Pellets
6. Castic silica

Upper Dayton limestone of Ohio
1. Clear dolomite rhombs penetrating fossil fragments composed of calcite
2. Platy marcasite
3. Glauconite
   a) Castic
   b) Fossil casts
   c) Porous

Zone *B*, lower Osgood shale of Indiana
1. Bladed marcasite
2. Cubic parallel growths of pyrite, pyrite cubes
3. Porous glauconite
4. Finely castic silica
5. Cloudy fossil fragments composed of carbonate

Zone *C*, coarsely crystalline Osgood limestone of Indiana
1. Rounded fragments of fossils in a groundmass of fibrous carbonate
2. Pyrite
   a) Cubic parallel growths
   b) Elongated cubes
   c) Pyritized crinoid stems
3. Porous glauconite
4. Silicified crinoid stems

Zone *D*, middle shaly Osgood limestone of Indiana
1. Sponge plates
2. Glauconite pebbles
3. Large grains of quartz sand
4. Cubic parallel growths of pyrite, pyrite cubes

TABLE 4—*Continued*

5. Foraminifera
   a) *Lituotuba exserta*
   b) *Ammodiscus incertus*
6. Finely castic silica

Zone *E*, upper Osgood shale of Indiana
1. Marcasite, blocky or platy
2. Foraminifera
   a) *Lituotuba exserta*
   b) *Ammodiscus incertus*
   c) *Ammodiscus exsertus*
3. Large grains of quartz sand
4. Cloudy fossil fragments composed of carbonate
5. Finely castic silica

Osgood shale of Ohio
1. Bladed marcasite
2. Cubes, octahedra, cubo-octahedra of pyrite
3. Porous glauconite
4. Quartz sand grains
5. Finely castic silica

Zone *F*, upper shaly Osgood limestone of Indiana
1. Platy marcasite
2. Foraminifera (rarer types)
   a) *Thurammina triangularis*
   b) *Bathysiphon deminutionis*
3. Flaky glauconite
4. Finely castic silica

Zone *A*, Laurel limestone of Indiana
1. Large anhedral crystals of carbonate
2. Sponge plates
3. Foraminifera—*Ammodiscus incertus*
4. Cubes and octahedra of pyrite

Zone *B*, Laurel limestone of Indiana
1. Octahedra of pyrite
2. Castic silica

Zone *C*, Laurel limestone of Indiana
1. Sponge plates
2. Cubic parallel growths of pyrite
3. Glauconite
   a) Porous
   b) Pellets
4. Chert
5. Cubo-octahedra of pyrite

TABLE 4—*Continued*

Zone *D*, Laurel limestone of Indiana
1. Blocky marcasite
2. Sponge plates
3. Chert

Zone *E*, Laurel limestone of Indiana
1. Clear carbonate rhombs penetrating fossil fragments
2. Castic glauconite
3. Sponge plates
4. Sand grains

Laurel limestone of Ohio
1. Clear dolomite rhombs penetrating fossil fragments
2. Blocky marcasite
3. Sponge plates
4. Castic glauconite
5. Cubo-octahedra of pyrite

Zone *F*, Laurel limestone of Indiana
1. Parallel growth of pyrite octahedra resembling jackstones
2. Tinted fossil fragments and vugs containing chert altering to quartz
3. Octahedra of pyrite
4. Chert

Massie shale (Ohio)
1. Bladed marcasite
2. Flaky glauconite

Euphemia dolomite (Ohio)
1. Large anhedral dolomite crystals and numerous large vugs
2. Quartz
3. Botryoidal chalcedony

Lower Springfield dolomite (Ohio)
1. Small anhedral dolomite crystals and numerous small vugs
2. Cubes of pyrite

Upper Springfield dolomite (Ohio)
1. Small anhedral dolomite crystals and numerous small vugs
2. Pyritohedra of pyrite
3. Castic glauconite

Lower Cedarville dolomite (Ohio)
1. Large anhedral dolomite crystals and numerous large vugs

Upper Cedarville dolomite (Ohio)
1. Large anhedral dolomite crystals and numerous large vugs
2. Castic glauconite
3. Octahedra of pyrite
4. Finely castic silica

CONCLUSIONS

From the foregoing descriptions and discussions of the Niagaran rocks of southwestern Ohio and southeastern Indiana certain general conclusions may be drawn. These conclusions follow.

1. The minerals of the Niagaran units are chiefly authigenic, but small amounts of detrital minerals are present.

2. Micro-organisms are present in almost all units, the chief ones being arenaceous foraminifera and sponge spicules.

3. The Euphemia, Springfield, and Cedarville dolomites are true dolomites, whereas the Dayton and Laurel limestones are dolomitic limestones containing 78.06 and 87.19 per cent of dolomite, respectively. These conclusions are supported by chemical analyses and examination of stained powders.

4. The lower part of the Dayton limestone of Ohio is equivalent to the entire Dayton limestone of Indiana; the Osgood shale of Ohio is equivalent to the upper Osgood shale of Indiana (Zone *E*); and a portion of the Laurel limestone of Indiana (Zone *E*) is equivalent to the entire Laurel limestone of Ohio. These conclusions are based on similar foraminifera and insoluble-residue content of the Dayton limestone, and on similar insoluble residues of the Osgood and Laurel units. Moreover, the textures of the Laurel in the two states are similar. The Dayton correlation is at variance with the accepted correlation, since the entire Dayton of Ohio has been considered equivalent to the Dayton of Indiana.

5. Viewed from the concept of the formation of modern glauconite,[4] the water in which the Niagaran sediments were deposited appears to have varied in depth between 150 and 500 feet, the purer limestones being deposited in the deeper water, the shaly limestones and shales in shallower water. Three conditions are suggested: (1) relatively shallow water, probably between 200 and 450 feet in depth, indicated by the formation of shaly limestones accompanied by relatively large amounts of glauconite; (2) shallower water, probably less than 200 feet deep, indicated by the deposition of sparingly glauconitic shales; and (3) deeper water than in either of the pre-

[4] W. H. Twenhofel, *Treatise on Sedimentation* (2d ed.; Baltimore: Williams & Wilkins Co., 1932), pp. 456 and 457.

ceding cases, probably over 450 feet in depth, indicated by sparingly glauconitic, purer limestones and dolomites.

6. Petrographic methods are a useful aid in solving stratigraphic problems. In this problem the scarcity of sand grains indicates that either these Niagaran sediments were deposited far from shore, or if shores were not far away they were low; the varying amount of glauconite in the units suggests deposition of sediments at varying depths; the microscopic textures give some indication of the conditions of deposition and of subsequent changes in the rocks; and both textures and the distribution of the insoluble residues and microorganisms have led to the recognition of single units and to the conclusion that certain units are equivalent.

ACKNOWLEDGMENTS.—The writer wishes to acknowledge the aid and counsel of Dr. J. Ernest Carman, of the Ohio State University, who suggested the investigation, and of Dr. C. A. Lamey, who directed the petrographic work.

MODES OF RETREAT OF THE PLEISTOCENE ICE SHEETS

ERNST ANTEVS
GLOBE, ARIZONA

ABSTRACT

The Pleistocene ice sheets receded by melting, evaporation, and calving in the marginal belt, while the ice surface in the interior was lowered by evaporation and outflowage of ice. The wastage decreased from the edge toward the center. The zone of melting ranged perhaps from 25 to 100 or more miles in width. For the most part the retreating ice sheets had a firm, continuous, gently to steeply rising edge; but especially in transversal valleys, separated by high ridges, there was formed a belt of stagnant ice, rarely, if ever, as much as 10 miles broad. Contrasting of "downwastage" with "recession" has no physical basis.

In a recent paper on the mode of the late Glacial ice waning in New Hampshire Professor Goldthwait eagerly repudiates what he observed and wrote prior to 1929 and cheerfully goes to battle without ascertaining whether the attacked views are real or fancied.[1] Following Professor R. F. Flint, Goldthwait contrasts "downwastage" with "recession" (p. 347). His idea of the supposed differences is conveyed by statements like the following:

Downwastage of the ice surface almost to the valley floors instead of orderly "retreat" of a single wall or "front" [p. 347]; The downwastage of a thin and ragged ice margin instead of the northward retreat of a high ice "front" [p. 350]; Was the ice in the valley wasting away more by backward recession or by thinning over a zone five, twenty-five, or fifty miles wide? [p. 353]; It is conceivable that ablation may have thinned the ice down to almost nothing, with gentle southward slope over wide areas of upland while ice still remained fairly thick and partly stagnant in the broader and deeper valleys; and that finally the extremities of the valley remnants wasted northward at rates which Antevs has worked out [p. 357]; In North America Antevs' studies of the ice retreat . . . . leaving almost unmentioned the probable lowering of the surface of the ice sheet by areal wastage [p. 360]; and, If it should appear that the amount of water delivered to the sea by ice melting during the decline of the ice age depended more upon downwastage of the surface than upon final recession of the ice margin, it is not easy to judge correctly the stage reached by rising sea-level for any given position of the ice border [p. 369].

[1] J. W. Goldthwait, "The Uncovering of New Hampshire by the Last Ice Sheet," *Amer. Jour. Sci.*, Vol. XXXVI (1938), pp. 345–72.

Thus, according to Goldthwait's understanding, "downwastage" of an ice sheet is ablation of the marginal zone, 5 to many miles wide, to form a thin, ragged, crevassed, and stagnant fringe. "Recession," on the other hand, is withdrawal of a high ice cliff strictly by destruction of the very front, without lowering of the ice surface in the marginal belt or in the interior. Moreover, this is supposed to be the present writer's perception of ice recession. However, it is not, as is evident from published discussions of the factors and modes of ice waning, the width of the marginal zone of melting, the surface slope of ice sheets and its conditions, and other relevant problems which Goldthwait does not quote.[2]

COMMENTS ON PROBLEMS DISCUSSED BY GOLDTHWAIT

Climate undergoes changes in waves or pulsations, not along a straight line. The late Glacial ice recession, as chiefly controlled by the snowfall on the ice sheet and by the temperature at the border, varied greatly in rate, as abundantly recorded by moraines, varved clays, etc. Halts and readvances were natural, not irregular, phenomena, so much so that if no evidence of them is found in a wide belt it is likely owing to crudeness of the observations or to mistakes in the interpretation.

PROBABLE ICE READVANCE AT CLAREMONT, NEW HAMPSHIRE

According to the varved clays in the Connecticut Valley the uncovering of the 12 miles between Charlestown and locality 61, 3 miles north of Claremont, took more than two hundred and seventy plus one hundred years, or averaged less than 171 feet a year.[3] In contrast the rate of the ice recession in the Bellows Falls region just to the south reached 370 feet, and that in the belt north of locality 61 averaged 615 feet a year. Beyond proving this marked retardation at Claremont the varve records do not go, because of lack of clay and lack of exposures in the valleys from the Mohawk to the Merrimac.

[2] Ernst Antevs, "Retreat of the Last Ice Sheet in Eastern Canada," *Geol. Surv. Canada Mem. 146* (1925), pp. 45–56 and 93; *The Last Glaciation*, "Amer. Geog. Soc. Research Ser.," No. 17 (1928), pp. 54–73; "Late Glacial Correlations and Ice Recession in Manitoba," *Geol. Surv. Canada Mem. 168* (1931), pp. 25–28.

[3] Antevs, *The Recession of the Last Ice Sheet in New England*, "Amer. Geog. Soc. Research Ser.," No. 11 (1922), pp. 22, 28, 41, and 81–83; Pl. IV.

However, at about the same time, to judge from the direction of the ice flow, deposits of varved clay were overridden by a readvance of the ice at two known points on Lake Winnepesaukee.[4] There was probably a readvance of the ice edge at Claremont simultaneously with that recorded on Lake Winnepesaukee. This is concluded because the gravel discordantly overlying the varved beds at locality 41, 4 miles south of Claremont, probably is outwash, as it contains boulders over a foot in diameter, has not been observed elsewhere, and the old river gravels of the region are of the regular pebbly kind. Whether or not some drift ridges in the intervening region are moraines[5] is of no great significance.

THE ICE OSCILLATION AT THE COMERFORD DAM, VERMONT–NEW HAMPSHIRE

The Connecticut Valley ice lobe returned to a point near the junction of the Connecticut and Passumpsic rivers about two hundred and eighty years after the original uncovering, as determined by the varved clays[6] and later verified by Crosby[7] and Lougee[8] in the extensive cuts opened during the construction of the Comerford Dam. Since the readvancing ice lobe near its extreme limit deposited a till bed 70 feet thick, it must have had considerable areal extent and should have left a record at its limit of advance. The deposits most probably marking this limit are, as Crosby suggested, the moraines at Partridge Lake and between Littleton and Wing Road, 6 and 13 miles east of the dam, respectively.

THE OBSCURITY OF THE MARINE LIMIT

Goldthwait writes, on page 368: "If we now apply the theory that the ice sheet uncovered the coast by thinning down upon it, the late Glacial blanket of ice comes to have a new meaning, and the zone thus shielded from wave action acquires a breadth and degree of permanency that seems adequate," viz., to explain the obscurity of the marine limit. This assumption seems to be largely invalidated

[4] *Ibid.*, p. 81. [5] Goldthwait, *op. cit.*, p. 350.

[6] Antevs, "The Recession of the Last Ice Sheet in New England," p. 83.

[7] I. B. Crosby, "Extension of the Bethlehem, New Hampshire, Moraine," *Jour. Geol.*, Vol. XLII (1934), pp. 411–21.

[8] R. J. Lougee, "Time Measurements of an Ice Readvance at Littleton, N.H.," *Proc. Nat. Acad. Sci.*, Vol. XXI (1935), pp. 36–41.

for two reasons. The ice border ending in the sea was attacked by waves and the buoyancy of the water, which induced calving, so that the ice edge may have retreated rapidly in the form of a cliff. In the second place, shore features are still more obscure at the levels between the marine limit and the modern shore, though here no supposedly protective ice can be invoked.

ICE THINNING AND CHANGES OF LEVEL

On page 369, in passages partly quoted above, Goldthwait assumes that the present writer has failed to consider a lowering of the surface of the receding ice sheet and its implications on the crustal upwarping and the rise of sea-level, namely, upwarping prior to the uncovering and restoration to the ocean of more water than had been contained in the ice outside a given ice margin.

Gradual thinning in the interior of a retreating ice sheet by evaporation and outflowage in response to the areal decrease I have taken as a matter of course, and it did not occur to me that anybody could believe that the receding ice edge approached the Labrador center as a precipice $2\frac{1}{2}$ miles high; but whether directly mentioned or not, interior lowering, as well as marginal melting and evaporation, has been duly considered both in my discussions of the crustal movements and in the curve of the late Glacial rise of sea-level.[9]

PHYSICAL CONDITIONS AND MODES OF ICE RETREAT[10]

Ice-margin retreat takes place when wastage of ice exceeds nourishment. An ice sheet ending on land dissipates by melting and evaporation. Melting, the most important agency, is limited to those parts of the ice surface (fissures and bottom) that are warmed to 32° F. and is greatest at the ice border, while evaporation occurs both at low and at high temperatures and from the entire surface of the ice sheet. Since both thaw and evaporation are greatly dependent on temperature, the ablation, or surface depletion, decreases from a maximum at the ice edge to a minimum on the cold and calm central parts. An ice edge terminating in water also is wasted by

[9] Antevs, "Late Quaternary Changes of Level in Maine," *Amer. Jour. Sci.*, Vol. XV (1928), pp. 319–36.

[10] Antevs, "Retreat of the Last Ice Sheet in Eastern Canada," *op. cit.*; *The Last Glaciation;* "Late Glacial Correlations and Ice Recession in Manitoba," *op. cit.*

subwater melting and by severing of icebergs through wave action and the buoyancy of the water.

The width of the zone of melting of the Pleistocene ice sheets evidently varied with temperature and insolation, being greatest at low latitudes and far from sea fogs. In the northern states and southern Canada the width perhaps ranged from 25 to 100 or more miles, for on the modern Greenland ice cap the snow line—the upper limit at which the annual snow is all melted—ranges from sea-level to probably about 4,900 feet altitude 50 miles inside the ice edge.

Ablation of a sloping marginal zone first exposed the summits of mountains and hills. Thereafter the ice wasted faster over the highlands than over the lowlands because of absorption of heat by the exposed ground and its transmission to the ice. A debris cover could not very well be washed down onto the lowland ice to retard its melting, as sometimes suggested, since the surface of this ice, with the exception of the very border, would continuously lie above the lowermost ice-free land on the hillsides.

Topography and differential ablation tended to split the marginal ice into valley tongues. The ice became stagnant in transversal valleys when the ice sheet had become too thin to push supply over the ridges. If the valleys contained lakes of some depth the ice remnants were soon broken up by calving, but in other cases the disintegration of the detached ice bodies solely through ablation took some time.

In valleys or basins parallel to the general ice movement the here accelerated flow tended further to extend the ice lobes. However, most such valleys contained lakes which received great amounts of meltwater inducing extensive calving. Owing to this condition the ice edge normally was firm and clifflike and changed in outline from lobate in the southern or distal part of the valley, through straight, to re-entrant in the northern part. Perhaps most features in radial valleys, by some ascribed to stagnant ice, were rather caused by landslides, which clearly were common and of great topographic importance when the rivers cut into the late Glacial lake beds, whose greasy and slippery winter laminae formed matchless glide planes.[11]

[11] Hans Reusch, "Jordfaldet ved Mörset i Stjördalen," *Norges Geol. Undersökelse, No. 32* (1901), pp. 33–44; Gustaf Frödin, "Jordskreden och markförskjutningarna i

For the most part the Pleistocene ice sheets during their retreat had a distinct, solid, gently to steeply rising border comparable to that of modern ice caps. The marginal belt wasted by differential melting and evaporation, and the surface of the interior was lowered by evaporation and outflowage, so that the ice sheet retained the characteristic cross-section profile of a watch crystal.

In some regions there was a belt of stagnant ice off the continuous ice edge. The existence of such a zone and its width depended on the trend and degree of the relief, the rate of the forward motion of the ice, the attenuation of the marginal belt of the ice sheet by melting and undernourishment, the rate of retreat of the solid ice edge, and the durability of the severed ice blocks. Stagnant ice evidently occupied only a fraction of the width of the zone of melting. For instance, if the severed ice blocks lasted for seventy-five years, and the rate of retreat of the continuous ice edge was fifteen years to a mile (nine years to a kilometer), the width of the stagnant ice zone was 5 miles (8 km.). The fact that a belt of dead-ice topography may be 25 or more miles wide does not imply that there was so broad a belt of stagnant ice at any one time.

Therefore, the immoderate views which have contrasted ice retreat with downwastage have no physical foundation. The actual role of dead ice was well appraised by Salisbury thirty-seven years ago:

> During the dissipation of an ice sheet considerable masses of ice appear to have lost, or to have essentially lost, their motion. This happened especially in mountainous tracts, where the ice in the depressions became isolated, when that on the surrounding elevations was melted. Such isolated bodies of ice doubtless preserved their motion, in many cases at least, for a time. But when they became small, or when the local topography was unfavorable to motion, they became stagnant, and all the drift they held was let down on the surface as the ice melted.[12]

Göta Älvs dalgång mellan Trollhättan och Lilla Edet," *Meddel. Kungl. Svenska Vattenfallsstyrelsen No. 19* (1919); M. E. Wilson, "Arnprior-Quyon and Maniwaki Areas, Ontario and Quebec," *Geol. Surv. Canada, Mem. 136* (1924), p. 10; D. A. Nichols, "Landslides in Canada," *Canadian Field-Naturalist*, Vol. XLII (1928), pp. 212–20.

[12] R. D. Salisbury, H. B. Kümmel, C. E. Peet, and G. N. Knapp, "The Glacial Geology of New Jersey," *Geol. Surv. New Jersey*, Vol. V (1902), p. 86.

LOWER PALEOZOIC UNCONFORMITIES NEAR DRAPER, VIRGINIA, AND THEIR SIGNIFICANCE[1]

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ABSTRACT

Five unconformities occur within Ordovician formations exposed in the vicinity of Draper, Virginia. They are readily accessible from adjacent highways, U.S. Route 11 and State Routes 100 and 101, and the field relationships of the involved strata are revealed with unusual clarity. Their bearing upon the interpretation of unconformities is discussed.

INTRODUCTION

The locality under consideration is situated in central Pulaski County, in the Appalachian Valley, approximately 10 miles north-

FIG. 1.—Index map showing location of Draper, Va.

west of the Blue Ridge Plateau and 60 miles southwest of Roanoke, Virginia (see Fig. 1). It forms the southeastern part of an extensive fenster in the Pulaski and Max Meadows overthrust sheets. The nearly vertical strata exposed at Draper pass beneath these overthrust masses about ½ mile east of the town (see Fig. 2).

[1] Published with the permission of the state geologist of Virginia.

STRATIGRAPHIC SUCCESSION

Table 1 shows the most nearly complete sequence of formations occurring in the vicinity of Draper. The stratigraphic positions of these beds have been carefully established by Butts[2] and others. The Canadian-Chazyan disconformity, which is so apparent in the eastern half of the United States, is here indicated by the absence

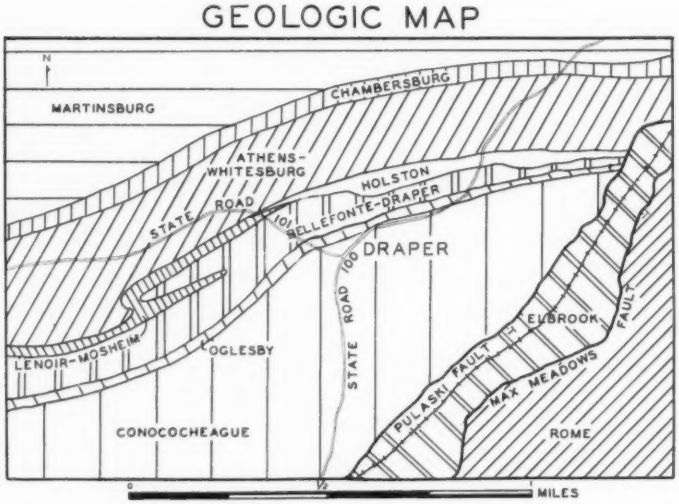

FIG. 2.—Areal geology in the vicinity of Draper. The strata north of Draper are approximately vertical, and the areal pattern of the formations makes a natural columnar section.

of the Murfreesboro limestone of early Stones River age and by the absence of the Buffalo River beds of post-Canadian, pre–Stones River age. The Murfreesboro is represented by several hundred feet of limestone in the northwesternmost belts of the southern Appalachian Valley, but the Buffalo River group is not known to be present except in Missouri and portions of adjacent states.

Figure 3 shows the stratigraphic succession of lower Ordovician

[2] Charles Butts, "Geologic Map of the Appalachian Valley of Virginia with Explanatory Text," *Va. Geol. Surv. Bull. 42* (1933), pp. 10–20.

strata near Draper. It will be noted that there are several variations from the idealized column given in Table 1. The Ottosee and Moccasin formations are absent. Moreover, in some localities near Draper the Whitesburg lies directly upon the Lenoir, whereas in

TABLE 1*

IDEALIZED SECTION OF ORDOVICIAN ROCKS OF NITTANY TO UPPER BLACK RIVER AGE PRESENT IN SOUTHEASTERN BELTS OF SOUTHERN APPALACHIAN VALLEY OF VIRGINIA

System	Series	Group	Formation	Thickness in Feet
Ordovician	Mohawkian	Black River	Chambersburg	180
			Moccasin	250
	Chazyan	Blount	Ottosee	150
			Athens	1,000
			Whitesburg	25
			Holston	250
		Stones River	Lenoir	100
			Mosheim	25
	Hiatus and disconformity			
	Canadian		Bellefonte	50
			Nittany	600

* All these formations can be found within 20 miles of Draper.

others it lies upon the Holston. The Holston, where present, lies upon an erosional surface carved into the underlying Lenoir, Mosheim, Bellefonte, and upper Nittany[3] beds. The erosional break between the Mosheim and the underlying Bellefonte is also apparent.

[3] The writer has recognized two members of the Nittany in the Draper Mountain area: a lower limestone member and an upper division composed of dolomite. The lower or Oglesby member is about 155 feet thick. The overlying Draper member is approximately 350 feet thick. These new divisions are described in a manuscript now in press (*Va. Geol. Surv. Bull. 55*).

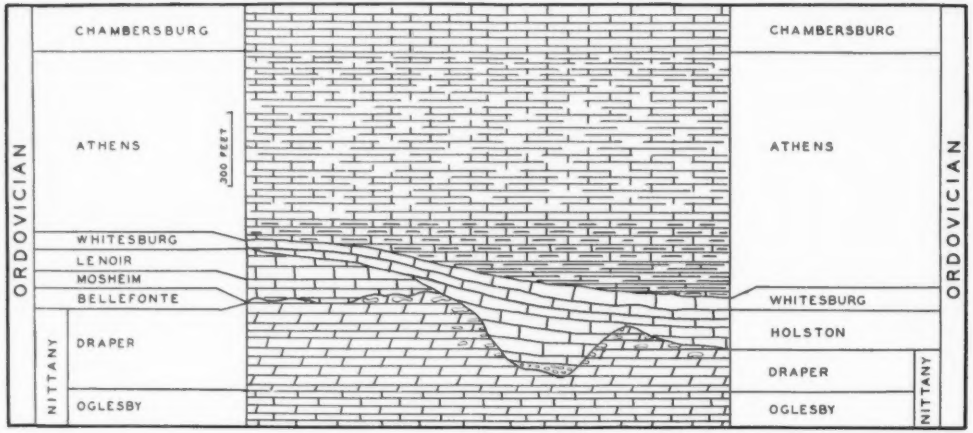

FIG. 3.—Columnar section of Lower Ordovician beds near Draper. The succession on the left is exposed $\frac{1}{4}$ mile west of Draper and that on the right is seen $\frac{1}{4}$ mile east of the town.

DISCONFORMITY BETWEEN THE BELLEFONTE AND MOSHEIM

North and northeast of Draper, both the Mosheim and the Bellefonte are missing as a result of post-Lenoir, pre-Holston erosion. However, both formations are present less than ½ mile west of Draper and are separated by an erosional unconformity. This break is indicated not only by the absence of the Murfreesboro and Buffalo River beds but by evidences of weathering and erosion along the contact. Locally the Mosheim lies upon the upper beds of the Draper dolomite, which fact indicates that 35–50 feet of Bellefonte beds were there removed by post-Bellefonte, pre-Mosheim erosion. In places where the Bellefonte is present, its complete silicification is believed to have resulted from weathering during this erosion interval.

UNCONFORMITY AT THE BASE OF THE HOLSTON

North and northeast of the intersection of State Routes 100 and 101 the Holston lies on the lower beds of the Draper dolomite member of the Nittany formation. The lower 20 feet of the Holston is composed of cobbles of Nittany and Bellefonte chert and of limestone conglomerate containing pebbles of Nittany and Bellefonte dolomite and Lenoir and Mosheim limestones. This coarse accumulation is restricted to the deepest portion of the erosional trench within which the Holston lies (see Fig. 4). Followed westward, the base of the Holston rises stratigraphically, and near State Road 101 the Holston lies upon the upper Lenoir. From this point east to the place where the Holston lies upon the lower beds of the Draper dolomite, a distance of approximately 1,000 feet, the erosion surface at the base of the Holston has been cut down through 90 feet of Lenoir, 35 feet of Mosheim, 50 feet of Bellefonte, and approximately 275 feet of Draper dolomite, to within 75 feet of the base of this member. The great relief of this erosional surface of unconformity and the conglomeratic character of the basal Holston suggest considerable weathering and erosion prior to the deposition of the Holston. However, the fact that the surface of unconformity cuts beds as young as the Lenoir indicates that this period of erosion did not begin until after Lenior time. Since a rather complete section of Holston lies within this depression, the erosion must have been ac-

complished prior to most of Holston time. If the post-Lenoir, pre-Holston interval was of considerable duration, somewhere a sedimentary record of this time should be found intercalated between the Lenoir and Holston. No beds are known to intervene between these two formations in any part of the Appalachian region, and they have been generally considered conformable units.

FIG. 4.—Basal Holston chert conglomerate exposed north of Draper. Photograph by Arthur Bevan.

West of Draper a fairly full sedimentary record of Lenoir time is present. The Holston shows its thickest development in the very places where post-Lenoir erosion accomplished the most. Hence, the erosional surface upon which the Holston lies must have been carved in less than a stage of geologic time.

HIATUS BETWEEN THE ATHENS AND CHAMBERSBURG

The absence of the Ottosee and Moccasin formations between the Athens and Chambersburg indicates an interruption of sedimentation of considerable duration. In areas only 20 miles southwest of Draper, 400 feet of Ottosee and Moccasin intervene between the

Athens and the Chambersburg or its equivalents. A careful study of the Athens-Chambersburg boundary reveals a relatively smooth contact along which there are no evidences that the Athens was eroded during Ottosee or Moccasin time. Moreover, the uniform thickness of the Chambersburg tends to conceal the fact that that formation lies upon a surface of unconformity. From the contact itself one would not suspect that it involved any less continuity of deposition than any bedding plane in either the Athens or the Chambersburg. In reality this *apparently* conformable contact marks an important hiatus in the sedimentary record of this locality. Such a contact may be the result of an interim of nondeposition and nonerosion during Ottosee and Moccasin time.

HIATUS BETWEEN THE WHITESBURG AND LENOIR

Approximately $\frac{1}{4}$ mile west of Draper the Whitesburg lies directly upon the Lenoir. From their contact there is little evidence that the relationship between the two is one of unconformability. When this contact is traced eastward, a featheredge of Holston is found to intervene between the Lenoir and Whitesburg in exposures just east of State Road 101. More evidence of post-Lenoir erosion is found here than in exposures where the Holston is absent and the Whitesburg lies directly upon the Lenoir. This break is similar in its deceptive characteristics to the Athens-Chambersburg boundary.

LOCAL UNCONFORMITY AT THE BASE OF THE ATHENS

As shown in Figure 3, the Whitesburg and Athens are somewhat thicker north of Draper than they are west of the town. The trench cut during post-Lenoir, pre-Holston time was not entirely filled by Holston sediments. During Whitesburg time more limestone was deposited upon the Holston than accumulated upon the Lenoir in adjoining areas on the west. However, there is no evidence that the sedimentary record of Whitesburg time is any less complete where the Whitesburg is thin than it is north of Draper where the formation is thicker. Local variations in the rate of deposition in the Whitesburg sea can account for the local differences in thickness of the formation.

Marine currents, generated by the marked irregularity of the sea

floor, carried all the black muds accumulating in this vicinity into this depression, and Athens sediments did not accumulate on portions of the sea bottom contiguous to the depression until after it had been completely filled. Since sedimentation in early Athens time did not occur in areas bordering this depression, there is an unconformity of nondeposition at the base of the Athens in those places.

CONCLUSIONS

The relative amounts of time required to produce these five surfaces of unconformity cannot be inferred from the relief of their respective surfaces. The amount of relief on any surface of unconformity produced by subaerial erosion depends upon the stage of the cycle of erosion which is reached prior to resubmergence of the land. Subaerial erosion produces maximum relief during the mature stage, and long-continued erosion tends to reduce the land to a peneplain. Hence, some relatively smooth surfaces of unconformity may represent longer interruptions of sedimentation than some rugged ones. The maximum relief which can be developed in an area of new land depends upon the amount and rate of its uplift, upon the degree of induration of the emergent sediments, and upon the rate of erosion. A rugged surface cannot be produced if the land is elevated but a few feet above sea-level or if the rate of erosion is nearly equal to the rate of uplift.

Interruptions of sedimentation, such as that which occurred during early Athens time, do not imply any emergence or erosion. On lowlands bordering the sea and in the neighboring shallow water, the rates of erosion and sedimentation may be so slow that neither of these processes accomplishes much over long periods of time. The contacts of the Chambersburg with the Athens and of the Whitesburg with the Lenoir indicate, respectively, a minimum of both erosion and deposition during the Ottosee-Moccasin stages and locally during the Holston stage. Such might have occurred either on a lowland bordering the sea or in a sea whose waves did not erode appreciably and from whose clear waters little chemical or biochemical deposition took place.

FABRICATED DIAGRAMS

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ABSTRACT

Diagrams of superior quality may be produced speedily and at low cost by the use of Ben Day screens, multitone papers, transfer patterns, and set type. Descriptions of these manufactured aids, of their uses and limitations, are here outlined.

INTRODUCTION

Fabrication—manufacture from standard stock items—has long been used for rapid and economical construction in many fields. Recently Ben Day screens, multitone papers, transfer patterns, and other art aids, the standard parts for diagram assembly, have been made available to the small user.

Anyone able to draw a clean line with a ruling pen and a straightedge can fabricate diagrams. No special skill or equipment is needed, and the finished product is satisfying. Fabrication is especially useful in the rapid production of relatively simple figures. Complicated work such as large detailed contour maps, perspective block diagrams, and true sketches is best produced by the usual drafting methods.

Fabricated diagrams produced with reasonable care are superior to ordinary hand-drawn work but are slightly inferior to the best work of a highly skilled professional draftsman.

LETTERING

The most difficult problem confronting the average maker of diagrams is lettering, for many workers able to do wholly satisfactory line work cannot letter.

Lettering guides of several types are successfully employed in large drafting-rooms. The purchase of guides is hardly economical unless they are to be used "full time."

Gummed letters, needing only to be moistened and stuck into place, are widely used.[1] "Float letters," printed on a transparent,

[1] John L. Ridgway, *Scientific Illustration* (Stanford University: Stanford University Press, 1938), p. 101, Pls. XVII and XVIII.

self-adhesive medium, have been adopted by several government departments and are giving satisfactory service.[2] Letters printed on cellophane and coated with adhesive have recently been introduced for advertising use.[3]

Newspaper artists produce strikingly good-looking maps and diagrams on very short notice by the use of "pasteup" lettering. Whole words, printed to order, are cemented onto the drawing—a method requiring a minimum of skilled work. Similar methods may be used by the geologist, who should produce work of better than "newsprint" quality but can devote more time to his drawings. Spacing, in pasteup work, is automatically taken care of by the type-founder; application of words is simple and quick; costs are surprisingly low when the repeated use of most technical words is considered.

TYPE STYLE

Of the several hundred different type styles now available about half are legible enough for technical use. Choice of type depends, in general, on what the printer has in stock. Use of out-of-stock or odd-size type greatly increases printing costs.

Letters for use in technical diagrams must be simple, clear, and legible when reproduced. Complicated serifs, fine lines, and extremely acute angles are to be avoided. Types in which all lines composing a letter are of about the same width, such as "Copperplate Gothic" (Fig. 1), are most satisfactory.

The standard practice of printing names of land features in roman type and those of water features in italics can be followed when using pasteup lettering, for most type faces come in both roman and italic.

TYPE SIZE

No letter in a reproduced figure should be smaller than 1 millimeter high, according to several authorities.[4] Whenever possible, letters should be larger, a height of 1.5 millimeters, or about 1/16 inch, being the minimum for easy legibility.

[2] Not generally available at present. Used by the U.S. Geological Survey, the U.S. Navy Department, and others.

[3] Marketed under the trade name "Stack-tipe" by the Para Tone Co., Inc., 440 South Dearborn St., Chicago, Ill.

[4] Ridgway, *op. cit.*, p. 99.

Diagrams should be drawn considerably larger than they are to appear in print. Most photoengravers prefer copy twice as large as the finished figure is to be. If the engraver is supplied with a photographic copy of the original, some size reduction should be made in this process. Unless copy is reduced in size at each transfer, line work is "spread," producing an undesired heaviness in the final figure. These size reductions must be considered when drawing the lines and selecting the type for the original.

Words needing emphasis should be printed in type differing in size, style, or heaviness from that used for less important words.

FIG. 1.—A type card, printed to order, with wide spacing between the lines to allow for cutting apart and mounting. This type is 12-point Copperplate Gothic Heavy.

As a general rule, in small or medium-sized diagrams the largest letters should not be more than four times as high as the smallest. If greater size contrast is used, the smallest letters will be completely overshadowed and might as well be omitted.

SPACING

Type is normally set "slug to slug," giving a standard spacing between letters (Fig. 2, *C*). Whenever possible, this spacing should be used, as any other entails a considerable increase in the labor and cost of typesetting. With standard spacing the approximate number of characters that can be set in a linear inch may be found by measuring specimen type in the catalogue. If wider spacing (fewer characters per linear inch) is desired, the typesetter can put spacers

between the slugs. If narrower spacing (more characters per linear inch) is needed, condensed type must be used and spaced out, if necessary, to the specified length. When nonstandard spacing is needed, the length to which the words are to be set should be specified on the copy for the printer (Fig. 2, *A*). Costs will be greatly reduced if a tolerance of about 1/16 inch, plus or minus, is allowed.

PAPER

Any reasonably good paper capable of taking a clean impression can be used for titles. Usually the printer stocks, or can get on short notice, a printing paper similar to the drawing paper used. An

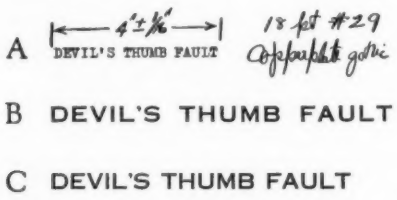

FIG. 2.—Type specifications and results. In *A* the copy is typewritten and the instructions handwritten. The length to which the type is to be set is specified above it, with the tolerance. The type set from this specification is shown at *B*. In *C* the same wording is set with standard spacing. Reduced one-half.

exact match is not necessary; any paper having about the same color and surface texture as the drawing paper will be perfectly satisfactory.

CHOICE OF PRINTERS

The printing of type cards is a small job and is best done in a shop equipped for small work, such as one specializing in visiting cards and stationery. Large printing houses, equipped to turn out large volumes of printed matter in a short time, do not want work of this type and cannot, in general, handle it profitably.

Whenever possible, thirty-six hours should be allowed for the printing of type cards, which must not be handled until the ink is thoroughly dry. More rapid work is possible, but costs, in general, are higher if speed is demanded and the quality of the printing lower.

APPLICATION

Type, cut from type cards, is attached to the drawing with rubber cement, which is preferable to either paste or glue since it does not

swell or warp the paper. When only a few diagrams are made at a time, cement in a brush-top tube is convenient and economical.[5]

Where type is applied over patterns, the edges of the paper should be carefully trimmed, producing a neat white margin around the words. In parts of the diagram that are otherwise white type need not be trimmed so carefully.

After trimming, the type is liberally coated on the back with rubber cement and put in place. While the cement is setting, the type

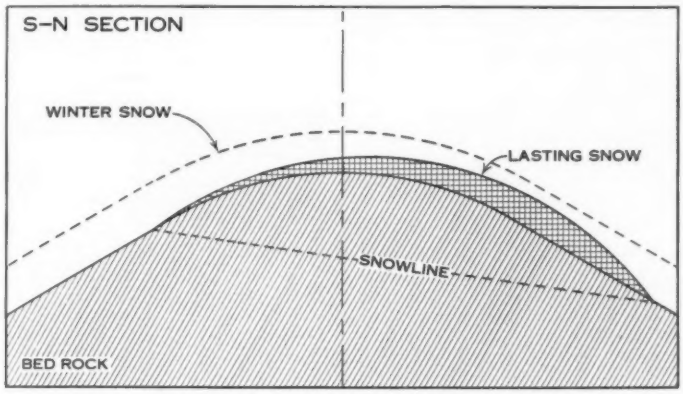

FIG. 3.—A typical fabricated diagram, with hand-drawn outlines, Ben Day patterns, and "pasteup" lettering. The original of this diagram was 14 inches long; the photographic copy from which the engraver made the plate for the published figure was 9 inches long.

can be "lined up" with the base of the drawing. Excess rubber cement is removed by gentle rubbing.

Figure 3 is a typical fabricated diagram with pasteup lettering. Here the words "bedrock" and "snowline" were of necessity carefully trimmed, while "winter snow" and "lasting snow" needed only to be separated from the rest of the card before cementing them in place.

SPECIAL SYMBOLS

In every branch of science special symbols, not made by type founders, are used. Most maps require a "North" sign and other conventionalized figures which are used repeatedly. These can be

[5] "Para-Lastik," made by Shaeffer's, Fort Madison, Iowa.

drawn once by a skilled artist, copied to the size desired, and cemented into place as needed. Figure 4 shows such a symbol.

When lettering must appear in black areas of a map, it is best to have the letters white on a black field. "Negative letters" (Fig. 5) may be made photographically. If only one copy is needed, the type may be photographed through a prism, using bromide paper instead of film. This, when developed and fixed, gives the desired white letters on a black field.[6] When several copies are needed, they are best printed photographically from a positive transparency, made

FIG. 4

FIG. 5

FIG. 4.—Much-used special symbols, such as the "North" sign here shown, may be duplicated photographically and applied as needed in the same manner as printed titles.

FIG. 5.—"Negative letters for lettering in black areas of a map."

by contact printing from a negative or by photographing the type on "direct positive" film.[7] Many copies of a special symbol, all the same size, are best printed from a line cut. Photographic reproduction is cheapest for less than about one hundred copies.

BEN DAY SCREENS

Ben Day screens are used to apply standard patterns over large areas. Basically, Ben Day, as it is called, is a transparent medium on which a pattern is printed in opaque ink. This material is fastened over the drawing, and unwanted parts of the pattern are removed by scraping or cutting.

[6] Ridgway, *op. cit.*, p. 59, Pl. XI.

[7] Made by Agfa-Ansco, Inc., Binghamton, N.Y., under the trade name "Agfa Direct Copy Film."

SCREEN TYPES

Two general types of Ben Day are in common use. The older, commercially known as "top sheet," is composed of sheet celluloid on which the pattern is printed in removable ink[8] (Fig. 6).

Recently, another type, known as "self-adhesive Ben Day," has been developed. This is composed of flexible cellulose sheeting (cellophane) on which the pattern is printed. Directly over the pattern a coating of waxlike adhesive is applied[9] (Fig. 7).

In the making of geological diagrams both types of Ben Day are useful. Top sheet is economical where large areas are to be patterned

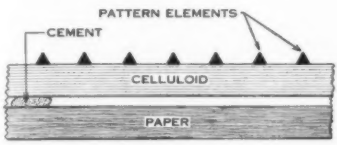

FIG. 6

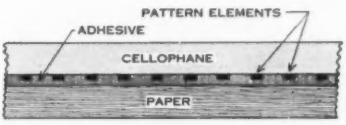

FIG. 7

FIG. 6.—Cross section of "Top Sheet" Ben Day in place on a drawing (greatly enlarged). With this type of Ben Day the pattern elements are exposed and must be protected from mechanical damage.

FIG. 7.—Cross section of self-adhesive Ben Day in place on a drawing (greatly enlarged). The pattern elements in this type of Ben Day are protected from mechanical damage by the cellophane base.

but must be handled carefully to protect the exposed pattern elements; it tends to attract dust as a result of static charges caused by friction during handling. Self-adhesive Ben Day is less subject to mechanical damage than top sheet and is especially useful where complicated curves must be followed. Top sheet can be used several times, if carefully handled; self-adhesive, in general, once only.

STANDARD PATTERNS

A few of the more than one hundred Ben Day patterns now manufactured are shown in Figure 8. Most of the patterns are available in several sizes and many of them in either "positive" (as shown in Fig. 8) or "negative" (white pattern on a transparent base, as shown

[8] Made by the Craftint Manufacturing Co., 210 St. Clair Ave., N.W., Cleveland, Ohio.

[9] Made by the Para Tone Co., Inc., Chicago, Ill.

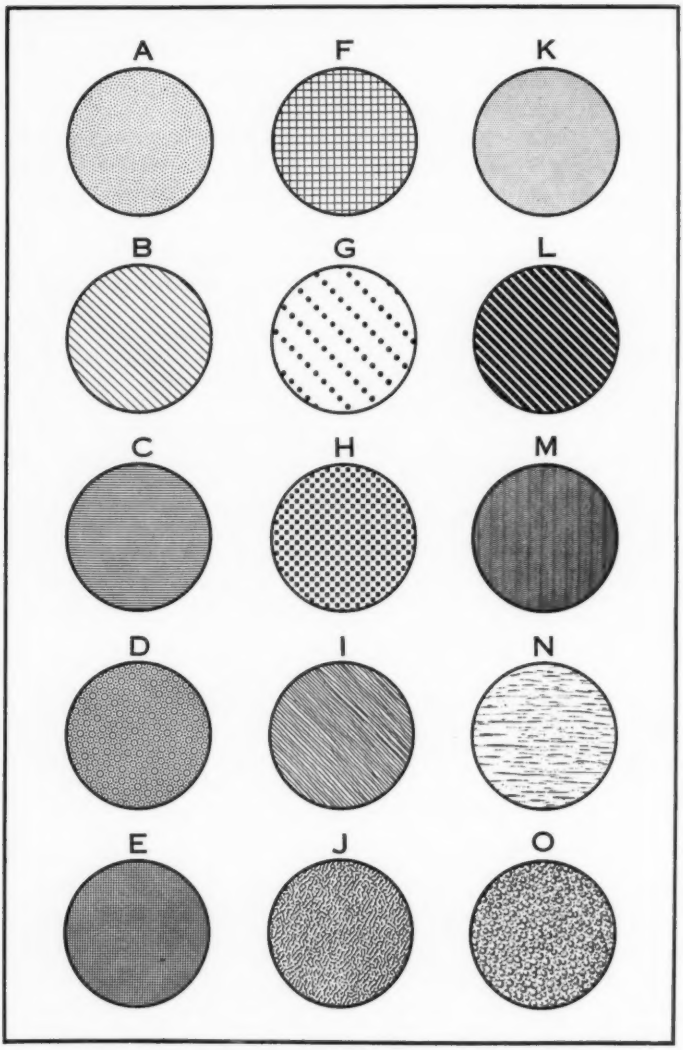

FIG. 8.—Various Ben Day patterns. Most of these are available in both "top sheet" and self-adhesive Ben Day.

in Fig. 9). Negative Ben Day is useful for lightening areas that are to be nearly black in the finished figure and is applied over solid black.

Some of the darker patterns in self-adhesive Ben Day are printed in transparent red ink, so that underlying lines can be seen through the whole patterned area while trimming. In copying (on process or engraver's films) the red pattern photographs as black. (*L* in Fig. 8 is a red screen.)

Screens may be described according to the arrangement of their pattern elements. *A* in Figure 8, for example, is a "random stipple," while *K* is a "regular stipple." *B*, *C*, and *L* are "rulings," *F* is a "cross-ruling," *D* is a "radial pattern," etc. Screens are usually ordered by the manufacturer's number rather than by description.

FIG. 9.—A dark area "broken up" by the use of negative Ben Day.

CHOICE OF SCREENS

The proper screens for a given diagram depend on the type of figure, desired appearance, and the amount of reduction which it must undergo.

Patterns as much like the conventional geologic symbols as possible should be used. For example, *A*, in Figure 8, is the standard symbol for sand or alluvium;[10] *B* closely resembles the symbol for bedrock; *C* can be used to represent shale; *K*, a regular stipple, closely resembles the symbol for sandstone, etc.

In general, screens as little alike as possible should be used for adjacent figure areas, and light screens, such as *A*, *B*, *F*, *G*, and *N* (in Fig. 8), are preferable to dark screens, such as *C*, *D*, *E*, *L*, and *M*, as light screens do not conceal much of the line work under them. Where one area must be emphasized, use of a screen much lighter or much darker than either of those adjacent will give the desired effect.

[10] Ridgway, *op. cit.*, Pls. XX and XXI.

Screens should be chosen with the final size of the figure in mind, as a screen reduced too much loses its pattern appearance and degenerates into a shade. If a number of patterns in a figure contain the same percentage of black, regardless of how it is divided and arranged, too much reduction will make all of them degenerate to similar grays and the figure will be confusing.

APPLICATION OF SCREENS

Screens are easily applied, but unless application is done carefully and to a reasonably good line drawing, the finished figure will

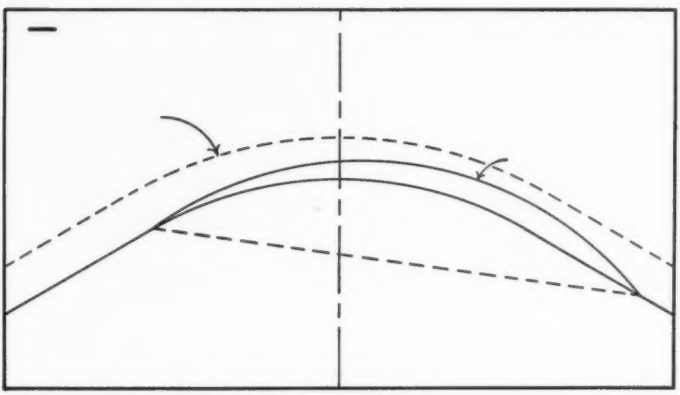

FIG. 10.—A line drawing ready for the application of Ben Day. Note that all lines are complete, including the hyphen in the upper left corner. See also Figs. 11 and 3.

be disappointing or unsatisfactory. Lines in the drawing must be firm, well inked, and wide enough to stand the necessary reductions. A line drawing ready for the application of screens is shown in Figure 10. Note that all line work in this drawing is complete. It is almost impossible to draw clean lines on Ben Day of either type.

Application of "top sheet."—Place the chosen screen upon the completed drawing, patterned side up, and cut away unwanted pattern areas. Remove the screen from the drawing, put a few "spots" of transparent rubber cement in the area to be patterned, and replace the screen, sliding it carefully into the exact position desired before the cement sets. Whenever possible the edge of the

screen base should coincide with a boundary line, so that the "edge shadow" will not have to be retouched out of the copy negative or tooled out of the cut. After the cement has set, undesired pattern elements are scraped away with a toothpick or a photographer's etching knife.

If the figure is to be copied under glass (the usual method), only enough cement need be used to hold the top sheet firmly in place, as the glass will keep the celluloid and paper in close contact during exposure. If type is cemented atop the Ben Day or if copying is to be done "out in the air," more careful cementing will be necessary.

The cement used to hold top sheet in place must be transparent when dry. Cements that yellow on drying photograph as dark gray or black, necessitating retouching and sometimes spoiling the figure.[11] Dust between the top sheet and the drawing introduces extraneous elements into the pattern and must be carefully guarded against.

Application of self-adhesive Ben Day.—Place the chosen screen upon the completed drawing, waxy side down, and rub the screen surface over the areas to be patterned with the fingertips to produce temporary adhesion. Cut away unwanted pattern areas with a sharp pocketknife or photographer's etching knife. Rub the whole screen area firmly with a burnisher to produce close and permanent adhesion. Wherever possible the trimming cut should follow the center of the line bounding the patterned area. Do not cut through the drawing when trimming the Ben Day.

Unwanted wax around the edges of the pattern can be removed with a cotton swab moistened (not saturated) in carbon tetrachloride, benzene, or other volatile solvent.

Dirt under self-adhesive Ben Day is undesirable. Particles of grit can sometimes be removed by "chasing" them to a transparent area and punching them out through the thin cellophane base.

A typical figure with Ben Day in place is shown in Figure 11. This, after type is cemented on, becomes Figure 3.

Joining sheets of like pattern.—Where large areas are to be patterned, several sheets of Ben Day must be joined together. In the

[11] Special cements, available at art-goods stores, are made for this work. Ordinary rubber cements are seldom satisfactory.

interest of neatness these joints should not show. Rulings, such as patterns *B*, *C*, and *L* (Fig. 8), can be joined quite easily wherever the pattern "runs out." Linear patterns of top sheet are joined by trimming adjacent edges parallel to the rulings and placing the sheets so that the spacing between their "outside" rulings equals that between the rulings in the pattern. A scrap of like-patterned Ben Day is a convenient spacing guide. With top sheet Ben Day, an "edge line," which must be retouched out of the copy negative, will be formed at the joint.

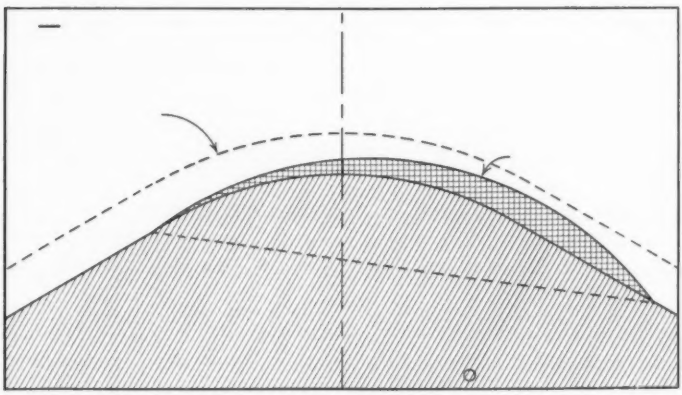

FIG. 11.—A line drawing after application of Ben Day. The lower pattern is *B* in Fig. 8, the upper is *F*. Cf. Figs. 10 and 3 for "step by step" development of a fabricated diagram.

To join ruled self-adhesive Ben Day trim the "outside" edge of the first sheet parallel to the last ruling and burnish it into place. Put the second sheet adjacent to the first, with its "outside" ruling coinciding exactly with that of the first, then trim the second sheet and burnish it into place. Trim away the overlapping screen at the joint and remove the excess adhesive. Such a joint was used in Figure 11 and may be detected between the two lines intersecting the small circle in the lower right.

Joining of random, radial, and cross-ruled patterns is more difficult and is best done at some line in the figure, such as a latitude, range, or section line, or along the course of a river, so that the

obvious break in the pattern does not distract the reader's attention. Undetectable joints in regular stipples and in some radial patterns can be made, but the labor involved is usually more costly than a larger sheet of Ben Day.

Structural lines.—Structural lines in drawings should not be obscured by superimposed pattern elements. In general, if the width of the line is twice that of the pattern element, there will be no obscuration. In many instances structural lines will need thickening where heavy patterns cross them, as in Figure 12.

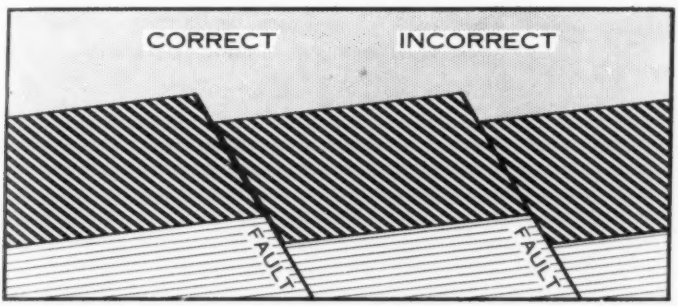

FIG. 12.—Treatment of structural lines

If a break occurs in the continuity of a feature, line patterns distinguishing that feature should break also. In Figure 12, showing the treatment of a fault, note how, in "incorrect," the pattern cuts directly across and partly obscures the structural line and how the heavy pattern (*L*, in Fig. 8) obscures the fault line much more than the light pattern (*B*, in Fig. 8). In the other part of the figure ("correct") the line patterns have been offset at the fault line, which has been thickened where the heavy pattern crosses it, minimizing obscuration.

Thickening of lines must be done somewhat arbitrarily, as there is no satisfactory rule telling just how much a line must be thickened so that it will not be obscured.

"Clearing" type and lines.—Where lettering or fine line work is covered by screens, some of the pattern elements may be removed to increase legibility. The effects produced when type and line work

are covered by a screen and the results of clearing by several methods are shown in Figure 13. Here the word "Dakota" has not been cleared, and the type, while legible, looks heavier than it actually is. Apparent "wobbles" in the thin line covered by the pattern and less apparent "wobbles" in the heavier line result from interference between the pattern elements and the lines.

Line work is cleared by removing the pattern elements over it. A metal-edged ruler is a convenient guide for the cutting tool. Cleared lines are shown to the right of obscured lines in Figure 13.

FIG. 13.—Clearing of type and linework covered by Ben Day.

The word "Pierre" has been cleared by the "pamplisest" method, in which the trimming tool follows the letter lines as closely as possible. Pamplisest clearing is most useful with top sheet Ben Day.

"Benton" was cleared by the "clean sweep" method, in which all pattern elements over and around the word are removed. This method is easily followed with either type of Ben Day and is especially useful where both inked and pasteup lettering are used, for type cleared by the clean sweep method almost exactly resembles, in the reproduced figure, that pasted atop the screens.

COMPOSITE SCREENS

By applying one screen over another an infinite number of patterns can be composed. Some of these have definite illustrative uses; others are rather messy. Theoretically, any number of screens can be used one over another; actually, it is difficult to get a satisfactory photographic copy of a figure having more than three screens over the drawing, for the base material of Ben Day is neither completely transparent nor uniformly refractive.

Composites of a single screen.—By applying the same pattern several times, each screen being either rotated or translated with respect to the one below it, a great variety of patterns can be produced. A few of the possible effects procurable by multiple applications of a simple ruling (*B* of Fig. 8) are shown in Figure 14. Pattern *C*, closely resembling *F* of Figure 8, is made by applying the ruling

twice, the second screen being rotated 90° with respect to the first. Removal of alternate verticals in each horizontal stratum of *C* (Fig. 14) produced pattern *D*, a close approximation to the standard symbol for limestone. By superimposing three screens (*A*, *F*, and *G*), each

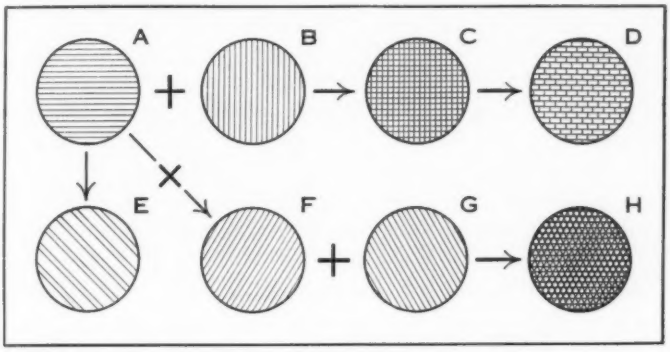

FIG. 14.—Patterns produced by multiple applications of a single screen

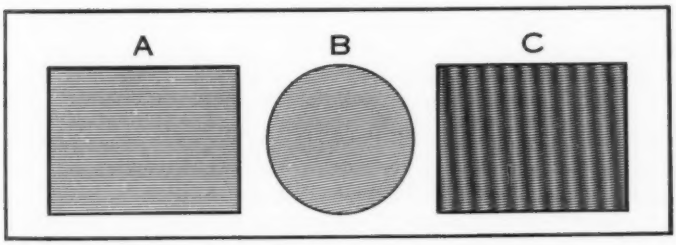

FIG. 15.—A simple *réseau* pattern, created by the superimposition of two line patterns at an acute angle.

rotated 60° with respect to the one under it, a triangular pattern, *H*, is produced. Removal of every third pattern line of *A* gives effect *E*. Patterns similar to *E* can be made by superimposing two like screens with the same orientation and translating the upper one any distance other than half the separation between lines.

When two rulings are superimposed with a slight angular difference between the rulings, a simple *réseau* pattern (Fig. 15) is pro-

duced. This figure, which is partly illusory, may be used to represent regularly varying features, such as banded strata. Illusions, which become important when the angle between rulings is small, make calculation of the features of a *réseau* pattern nearly impossible, and *réseau* effects are best secured by "cut and try" methods.

Special composite patterns, such as the "herringbone" of Figure 16, *A* and the "columnar offsets" of Figure 16, *B*, are made by assembling strips of Ben Day on the drawing, as shown in *A'* and *B'* of Figure 16. Construction of these rather striking patterns is quite laborious.

Composites of two like random patterns are usually very messy. When two like radial patterns are combined, the appearance is usually "cluttered" and the resultant pattern contains many offensive optical illusions.

Composites of unlike patterns.—When two unlike patterns are to be composited, the resultant pattern, in many instances, can be determined only by inspecting the superimposed screens. In general, the following will be found true:

Two unlike random patterns cannot be combined successfully.

A linear and a random pattern may be used together, but the composite is likely to appear "cluttered." *X*, of Figure 17, is composed of patterns *B* and *A* of Figure 8.

Two unlike linear patterns can be combined successfully, provided the angle between the rulings is greater than 30°. A smaller angle of intersection produces complicated *réseau* patterns. *Y* of Figure 17 is composed of patterns *B* and *C* of Figure 8.

A linear pattern cannot be successfully combined with a radial pattern, complex *réseau* patterns being produced. *Z* of Figure 17 is composed of patterns *D* and *C* of Figure 8.

Combinations of random and radial patterns almost invariably resemble smudged radial patterns.

Two unlike radial patterns used together produce a "wheels within wheels" effect, which, because of the optical illusions produced, is irritating to the average observer.

Successful combinations of three unlike nonlinear patterns are seldom made. Occasionally three unlike light linear patterns can be used together.

"Lateral composites," made by assembling strips or patches of unlike-patterned Ben Day side by side on a drawing (as is done with like-patterned Ben Day in Fig. 16), are of occasional illustrative value.

In general, although composite patterns are sometimes necessary, they should be made up of as few and as simple components as possible.

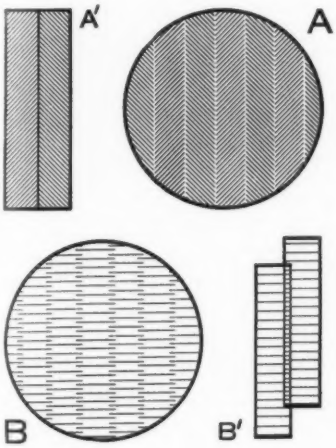

FIG. 16.—Special composite patterns

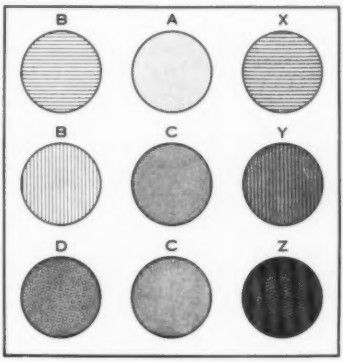

FIG. 17.—Composites of unlike patterns

SPECIAL SCREENS

In most branches of science special patterns are used to indicate certain features. Some of the most-used special patterns are commercially available, and patterns closely resembling some others are made. A few patterns because of their limited use cannot be commercially produced and must be drawn in by hand. When such patterns are used a number of times, but not often enough to justify the making and printing of a Ben Day pattern (i.e., an initial order of several hundred screens cannot be given), duplicate patterns, either positive or negative, can be produced photographically at a cost not greatly exceeding that of standard Ben Day.

Such a special pattern, as used in combination with standard-

patterned Ben Day, is shown in Figure 18. If only a small area containing a few elements is to be patterned, the use of special Ben Day is uneconomical, and the patterning is best done by drawing in the elements.

Manufacture of special Ben Day.—Special Ben Day is made by photographic copying of a hand-drawn master pattern. Figure 19 shows the positive and negative screens produced from a master-drawing, which was greatly reduced in copying to "drop out" the minor and unavoidable defects in drafting.

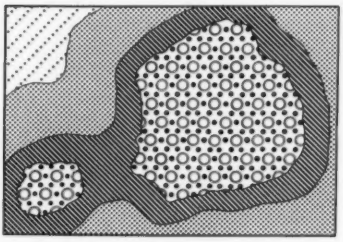

FIG. 18

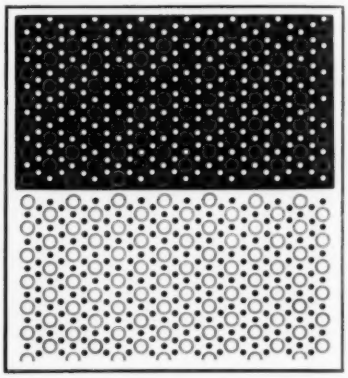

FIG. 19

FIG. 18.—A small geological diagram in which special and standard Ben Day are used. The two circularly patterned areas contain a special Ben Day pattern. From this, toward the upper left corner, are, in order, patterns *L*, *H*, and *G* of Fig. 8.

FIG. 19.—Special Ben Day, positive (lower section) and negative (upper section)

Upon completion, the master-drawing was photographed on engraver's film (Kodalith) and a positive transparency made. This resembles top-sheet Ben Day except that the pattern elements are not easily removable. From the original negative any number of positive transparencies may be made. Negative Ben Day is made by printing from a positive transparency of the original. Different sizes of special Ben Day may be produced from a single master-drawing by varying the reduction in copying.

Cost of special Ben Day is about one dollar a square foot, after the master-negative or transparency is made. Drafting cost depends upon the type of pattern and the fineness of the work.

Where the pattern, either positive or negative, need not be transparent, a paper print may be used at a saving in cost of about 50 per cent. Line work can be applied over this print if the surface is cleaned with alcohol to remove the greasy surface film.

Application of special Ben Day.—Paper prints of special Ben Day patterns are cemented in place with any good noncockling adhesive such as rubber cement. Transparencies are treated exactly as top sheet (see under "Application of Top Sheet"), except that, as the pattern elements are not easily removable, the edges of the transparency should be trimmed to coincide exactly with the boundary line of the patterned area. Clearing of special Ben Day transparencies is done with an etching knife. The surface of the celluloid where pattern elements have been scraped away will be rough and whitish but can be smoothed by applying transparent varnish or by putting a drop of glycerin on it just before copying.

TONED PAPERS

Special drawing papers, containing one or more patterns which can be brought out by chemical treatment after the ink work is completed, have recently been introduced. These papers are convenient for certain types of technical drawings and are economical where a large part of the figure area is to contain either a single pattern or two related patterns.

TYPES AND PATTERNS

Two general types of toned papers, marketed under the names "singletone" and "doubletone," are now available. Singletone paper, as its name implies, contains one latent pattern and is supplied in most Ben Day patterns (Fig. 8). Doubletone paper[12] carries two latent patterns, either of which may be brought out at will by chemical treatment. Four combinations may be secured with this paper—white, light tone, dark tone, and black (Fig. 20, *A*, *B*, *C*, and *D*, respectively). Doubletone paper is at present available only in rulings of different sizes, with the light tone a parallel ruling and the dark tone a cross-ruling.

[12] Made by Craftint Manufacturing Co., Cleveland, Ohio.

USE OF TONED PAPER

Where toned paper is used, an ink drawing is first necessary. This is made in waterproof India ink, and all line work must be completed before the tones are developed. With singletone paper the developer is brushed over the areas to be toned and blotted as soon as the tones appear. Do not let the developer dry on the paper. With doubletone paper the dark tones are produced by brushing on the dark-tone developer, which must be blotted as soon as the tones appear. After all the dark tones (cross-rulings) are developed, proceed with the light tones, using the light-tone developer and a different brush.

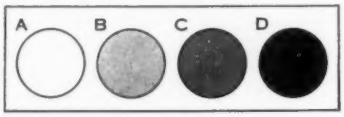

FIG. 20.—Tone potentialities with doubletone paper: *A*, white, as the paper appears before development; *B*, ruled, as the paper appears after development of the light tone; *C*, cross-ruled, as the paper appears after development of the dark tone; *D*, black, produced by inking or application of japan-and-lamp-black.

Blot these, also, as soon as the pattern appears, being careful that the light-tone developer does not spill over into dark-toned areas.

Where dark toning has been applied accidentally and light toning is wanted, the dark-tone elements may be bleached out by holding a cotton swab moistened with fuming hydrochloric acid over the areas to be bleached. Both tones may be bleached out with chlorine water or painted out with Chinese white. Keep toned papers away from chemical fumes and photographic darkrooms.

Clear, concise, detailed instructions, which must be followed if the products are to perform "as advertised," are supplied by the manufacturers of toned papers. Sloppy workmanship or attempts to "cut corners" lead to unsatisfactory results.

A simple physiographic diagram, patterned by the use of doubletone paper, appears in Figure 21. Line work for this figure was similar to that for Figure 10. Note the resemblance of Figure 21, patterned by the use of doubletone paper, to Figure 11, patterned with Ben Day.

Where more patterns are needed than can be secured with toned

paper but where its use is economical, Ben Day can be used in combination with paper patterns. Ink work and the development of the latent tones in the paper should be completed and the paper allowed to dry thoroughly before the Ben Day is applied.

OTHER AIDS

Many miscellaneous art aids are at present on the market. Their general use is to produce a pattern which appears as a solid gray but which can be reproduced by the relatively inexpensive line

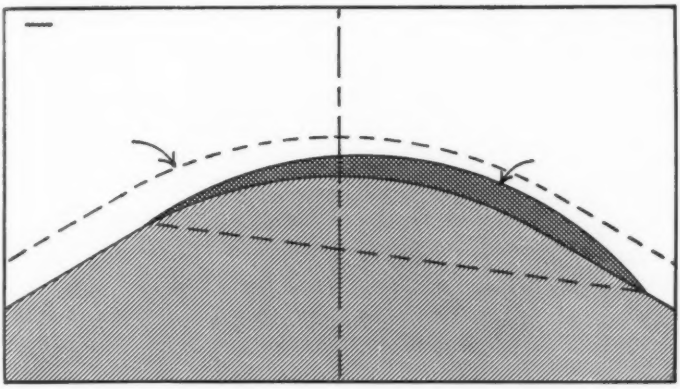

FIG. 21.—A simple diagram made on doubletone paper

process rather than by more costly halftone engravings. Two of these aids, transfer patterns and stipple board, have definite, although somewhat limited, uses in technical work.

TRANSFER TONES

Transfer tones, based on the carbon transfer principle, are a simple and rather crude method of applying patterns to drawings. Pattern elements are printed in carbon on a transparent base, and the whole is called a "transfer sheet." To apply, the sheet is placed, carboned side down, on the drawing and the upper surface rubbed hard, so that the pattern transfers to the drawing. To produce a darker pattern the sheet may be applied several times with a rotation or translation between applications (Fig. 22).

Single and double applications of transfer tones usually produce a reasonably satisfactory pattern; triple applications are seldom satisfactory.

Minor pattern imperfections and the difficulty of duplicating composite patterns limit the use of transfer tones to newsprint and other relatively coarse work.

STIPPLE BOARD

Stipple board is useful in paleontological and topographic drawing, as with it tones ranging from almost solid black to relatively pure white can be produced, and the shaded figure can be reproduced

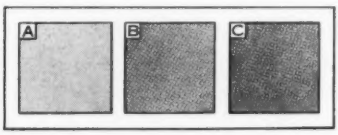

FIG. 22.—Transfer tones applied once (*A*), twice (*B*), and three times (*C*)

by means of a line cut. Stipple board is a rough-surfaced drawing board to which patterns are applied with a pencil or crayon, the surface pattern determining the arrangement of the pattern elements, while their size is controlled by the pressure with which the pencil or the crayon is applied. Figure 23 is a simple paleontological drawing made on stipple board. An excellent topographic drawing made on the same medium appears in Ridgway's *Scientific Illustration*.[13]

Results with stipple board are entirely controllable, and this aid, used with care, is a great timesaver.

COPYING

Fabricated diagrams in which Ben Day patterns, pasteup lettering, and other aids are used may be sent to the engraver "as is." As most diagrams are used several times and as errors and defects in the original can be corrected by retouching the copy negative or a print from it, copying is usually desirable. When a diagram is copied, the engraver receives a retouched print, needing little or no "fixing up," and the copy negative, from which additional prints may be made as needed, is retained.

[13] Fig. 13*C*, p. 94.

Unless the diagram-maker has adequate equipment and some photographic skill, copying is best left to a commercial photographer or planographer who is equipped to make copies quickly at low cost.

General copying techniques have been adequately described in many photographic treatises[14] and in some manufacturers' handbooks.[15] Special methods for copying fabricated diagrams will be briefly outlined.

Completed fabricated diagrams contain three layers—the upper surface, consisting of type, etc., cemented atop the Ben Day; the Ben Day pattern; and the surface of the drawing. A cross section of a fabricated diagram, ready for copying, appears in Figure 24. Contrast-increasing films and developers should be used so that the white surfaces of the drawing covered by Ben Day will appear the same shade as white surfaces not so covered. "All or nothing" films, such as process, Kodalith,[16] or Reprolith,[17] are suitable. Developers of the caustic type, such as Eastman D-8, assist in producing the desired contrast. Prints should be made on medium to hard glossy papers. Lighting must be uniform. If adequate diffuse daylight is not obtainable, photoflood lamps may be used.

Cameras for copying large diagrams must be of exceptional quality or distortion will be apparent in the copies. Small work may be done on any reasonably good camera, sharp definition being secured by using a

FIG. 23.—Sketch of a modern gastropod, *Turritella terebera* (Lamarck), made on stipple board.

[14] F. R. Fraprie and F. I. Jordan, *Photographic Hints and Gadgets* (Boston: American Photographic Publishing Co., 1938), pp. 246–51, 288–89, 297–98.

[15] *How To Make Good Copies*, on request from Defender Photo Supply Co., Inc., Rochester, N.Y.

[16] Made by Eastman Kodak Co., Inc., Rochester, N.Y. Kodalith is almost interchangeable with Reprolith.

[17] Made by Agfa-Ansco, Inc., Binghamton, N.Y.

small stop, such as F. 22. Most of the figures in this paper were copied with a 5×7-inch view camera.

RETOUCHING

As draftsmen who never make mistakes, printers whose work contains no typographical errors, and photographers who get "a perfect shot every time" are found only in the apocrypha of their respective professions, some retouching of almost every negative and print will be found desirable.

The most common flaws in copy negatives are shadows at the edges of pasted-on type, small flare spots, and indistinct lines. Pin-

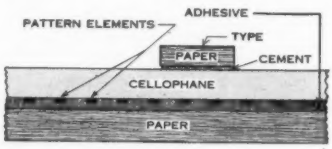

FIG. 24.—Cross section of a fabricated diagram, ready for copying

holes in negatives, causing small black spots on prints, are found when work is done in a dirty darkroom. These flaws can be corrected rather easily. Other flaws, such as improper contrast, large flare spots, and fuzzy focus, are so hard to correct that a new negative should be made. If all defects in a negative cannot be corrected by slight local reduction, spotting, or the scribing-in of a line, it is best to throw it out and make another. The common practice of spending an afternoon retouching a negative worth fifteen cents is foolish and wasteful.

RETOUCHING TECHNIQUES

Retouching, a specialized art in the case of portrait photography, is fairly simple when only defects in line copies are to be removed. Where copying is done by a professional, all photographic faults in the copy negative and usually all obvious defects, such as edge shadows, are removed by him.

Both negatives and prints can be retouched. Print retouching is usually easiest; but, if defects are not corrected in the negative, every print from that negative must be retouched. Where serious flaws appear in the copy, it is usually best to correct the drawing and make a new negative.

Print retouching.—Lines may be added to or removed from paper prints. Additions are best made first, as removal of features damages the paper surface so that clean lines cannot be drawn on it.

To insert lines, carefully clean the print surface with carbon tetrachloride or other nongreasy volatile solvent to remove the greasy film; then proceed exactly as on a drawing. If ink lines tend to smear, the print surface is greasy.

To remove lines, scrape them out with a photographer's etching knife, holding the blade at right angles to the print surface and taking off very small shavings at each stroke. Do not gouge out undesired features. Some workers[18] find that a Valet single-edged razor blade is a useful retouching tool.

Negative retouching.—Lines in the final copy can be either inserted or removed by working on the negative. Everything in negative retouching is just opposite to final conditions. A line in the print is represented by a transparent band in the negative.

Lines are inserted by scribing on the negative, the cutting tool, usually a photographer's etching knife, penetrating the silver-containing gelatin emulsion but not the transparent celluloid base. Where straight lines are to be scribed in, the etching knife can be guided by a ruler. Wide lines can be made by holding the etching knife slightly "sidewise" while making the scribing cut. Defective dots in stipple Ben Day can be nicked in with the sharp point of an etching knife or tooled in with a needle.

"Pinched" line work, caused by flare spots during copying, can be corrected in many instances by using a hypo-ferricyanide reducer ("Farmer's"),[19] which should be applied with a cotton swab, not with a brush, as a safety measure.[20]

Unwanted lines, edge shadows, and pinholes in the negative are painted out with opaque—a dense, quick-drying water color special-

[18] William Mortensen, *Print Finishing* (San Francisco: Camera Craft Publishing Co., 1938), pp. 40–47.

[19] C. E. K. Mees, *Elementary Photographic Chemistry* (Rochester, N.Y.: Eastman Kodak Co., 1936), p. 78; *American Annual of Photography, 1939* (Boston: American Photographic Publishing Co., 1938), p. 325. The whole subject of chemical treatment of negatives is covered in *Intensification and Reduction* by E. J. Wall (Boston: American Photographic Publishing Co., many editions).

[20] As most photographic workers habitually point brushes in their mouths, the use of a cotton swab for the application of poisonous chemicals will prevent accidents.

ly made for the purpose. Diluted opaque can be used in a ruling or other pen where especially fine work is necessary.

Figure 25, *A*, is a copy of a very poorly made fabricated diagram, containing about every fault possible. Figure 25, *B*, shows the im-

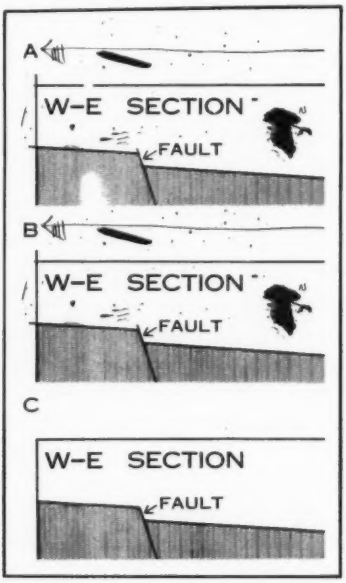

FIG. 25.—Stages in negative retouching

A. Copy of part of a simple diagram containing numerous defects. Note the missing line segment above "W–E," the extension of border and other lines beyond intersections, the careless trimming of the Ben Day—all drafting defects; the "bite" in the *O*, a typographical error; the specks and the flare spot in the Ben Day (lower left), photograpic defects; and the various specks and smudges due to careless handling.

B. Print from same negative as *A* after missing line segments were scribed into the negative and the flare spot in the Ben Day was reduced chemically.

C. Print from same negative as *A*, after scribing, reducing, and removal of unwanted transparent areas in negative (dark areas on print) by painting them out with opaque. This portion of the figure is now presentable, but it is neither as perfect nor of such high quality as a more carefully produced copy of a better executed original.

provement brought about by reducing the flare spot in the Ben Day and scribing in the missing line segments. Figure 25, *C*, shows the

finished print after unwanted dark areas have been whitened by painting the corresponding transparent areas in the negative with opaque. In this figure no print retouching was done. The opaque applied to Figure 25, *A*, to produce *C* is shown in Figure 26. Total retouching time was sixteen minutes.

SPECIAL METHODS

When complicated figures in which certain parts are to appear again and again, as in step-by-step developmental diagrams, are to be fabricated, various special methods will be found useful. These are

FIG. 26.—Opaque applied to negative of Fig. 25, *B* to produce print *C*. The opaque is gray, the unretouched negative areas are black, except where lines are to appear on print, in which case they are white (transparent). Note that the defective area in the Ben Day, from which the flare spot was chemically removed, is still visible in the retouched negative. This figure has been reversed (left for right) to facilitate comparison with Fig. 25.

all two-layer processes. The features which are to appear in all figures are first drawn, Ben Day applied, and type pasted on. After copying to the desired size, a positive transparency, reversed so that type "reads right" when viewed from the back (shiny side), is made. This is placed over glass, emulsion (dull side) down, illuminated from behind, the drawing paper placed over it, and the desired features added. When the paper work is completed, the transparency is placed, emulsion down, over it (as in Fig. 27), care being taken to see that lines in the transparency come over corresponding parts of the paper, and the whole is copied. This method is especially useful with toned papers.

When step-by-step figures are made, the copy, at each stage, should be from the altered original. If "cascade" copying is done (i.e., stage *A* is copied from the drawing, a print from *A* is altered and copied to produce *B*, etc.), the final figure of the series will bear little resemblance to the first figure, as a result of unavoidable alteration of line values in copying.

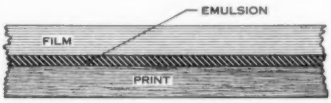

FIG. 27.—Arrangement of transparency and drawing for copying of "two-layer" figure.

FIG. 28.—Part of a large map produced by the "two-layer" method

Figure 28 is a section of a map produced by the two-layer method, the topographic features, patterns, and outlines being on the paper, while the type, latitudes, and longitudes are on the transparency.

SUMMARY

The steps necessary in the fabrication of a simple diagram may be briefly summarized as follows: (1) Plan the figure. (2) Order the type. (3) Do all ink work first—line work, hand or mechanically guided lettering, hand-drawn patterns. (4) Apply Ben Day or de-

velop paper tones. (5) Cement on type. (6) Check carefully for errors and defects. (7) Copy. (8) Retouch copy negative (if necessary). (9) Make and retouch print.

ACKNOWLEDGMENTS.—The writer is indebted to a number of printers, engravers, draftsmen, geologists, and manufacturers of art aids for assistance in the development of the methods outlined in this paper. Special mention is due Mr. William Calvert, of the Boulder Publishing Company, for technical assistance and a critical reading of this manuscript; Miss Katherine Ganse, of the Buffalo Press, for use of shop facilities; the University of Colorado Museum for use of photographic equipment; Mr. L. B. Pusey, of the United States Geological Survey, for valuable suggestions; and Dr. P. G. Worcester, of the University of Colorado, for a critical reading of this manuscript.

SLOTTED TEMPLET FOR RESOLVING CRUSTAL MOVEMENTS

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ABSTRACT

The slotted templet is a mechanical device to analyze crustal movements in an area of complex compressional structures. It is a network of strips that are slotted in one end and tied together by axles that slip in the slots. The length of the slot in each strip equals the amount of crustal shortening along the line of the strip. The rest of the strip represents the present length of the section. If the amount of shortening can be fairly well estimated, the slotted templet will show the movement of the individual points of the network in relation to one another and what the shape and size of the region was before deformation.

By means of the templet it can be shown that the diversely trending Laramide structures of the Wasatch–Great Basin region may all be related to an east-west regional compression, and the amount of shortening caused by the Willard thrusts is approximately determined as 13 miles. The original area included in the net is estimated as 24 per cent larger than the present area.

INTRODUCTION

If folds and thrusts curve through an azimuth of two or three right angles around small and large resistant elements, the divergent amounts and directions of local shortening present a mechanical problem of several aspects: (1) Are the local movements resolved components of regional shortening in one direction? (2) How did individual points move in relation to one another? (3) How large and in what shape was the region before deformation? The slotted templet is an apparatus designed to assist the geologist in the analysis of these horizontal movements. It is a network of strips that are slotted in one end and tied together with axles that slip in the slots. The network of strips corresponds to a network of sections on a map along which the amount of crustal shortening has been estimated.

The writer devised a slotted templet in 1936 to aid in an analysis of Laramide crustal movements in the Wasatch–Great Basin region,[1] and the same type of mechanism was worked out independently by Meyer[2] of the Fairchild Aerial Surveys, Incorporated, for the adjust-

[1] A. J. Eardley, "Structure of the Wasatch–Great Basin Region," *Bull. Geol. Soc. Amer.* (in press).

[2] William H. Meyer, Jr., "New Method of Mapping with Aid of Aerial Photographs and Slotted Templets," *Proc. A.I.M.E., 1939.*

ment of the points of triangulation networks of aerial mosaics. The problem to be solved was as follows: Move one point so as to satisfy known adjustments to several other points and also, perhaps, to move these other points so as to satisfy still a third group of points. The geological problem of crustal shortening is in principle the same.

PRINCIPLE AND CONSTRUCTION OF SLOTTED TEMPLET

Figure 1 is a map of an assumed area of compressional structure in which the amount of crustal shortening along certain sections has been estimated. It is desired first to find the position of B in relation to A and C. This may be done graphically by drawing an arc of 70 miles radius (60+10) from A and an arc of 80 miles radius (60+20) from C, in the direction of B. The intersection of the two arcs, B', is the position of B before crustal deformation.

If now it is desired to determine the former position of D in relation to A, B, and C, B' and C must be used as reference points from which to draw intersecting arcs toward D. If the problem is expanded to include the additional points, E, F, G, H, and K, the graphical method becomes unmanageable. A device that mechanically solves this problem may be easily constructed of slotted strips or templets representing each section and can be readily adjusted for different positions of the reference points.

In order to build a slotted templet for adjusting the points A, B, C, and D, cut a strip of rather stiff, heavy manila paper for each section according to the plan of Figure 2. The strips should be about $\frac{1}{2}$ inch wide, and each should have a slot accurately cut in one end equal in length to the amount of shortening along the section in question. The rest of the strip should correspond to the present length of the section. The strips are then tied together with axles that allow slipping along the slots as well as angular adjustment. Inverted thumbtacks with small disks of manila paper as nuts serve very well as axles.

The apparatus should be constructed to conform to the scale of a work map, and the map should be large enough so that the shortest strips are 3 or 4 inches long. The map used in the following example had a scale of 1 inch to 6 miles. The manner of adjustment of each templet is variable, and where adequate tie strips to make complete

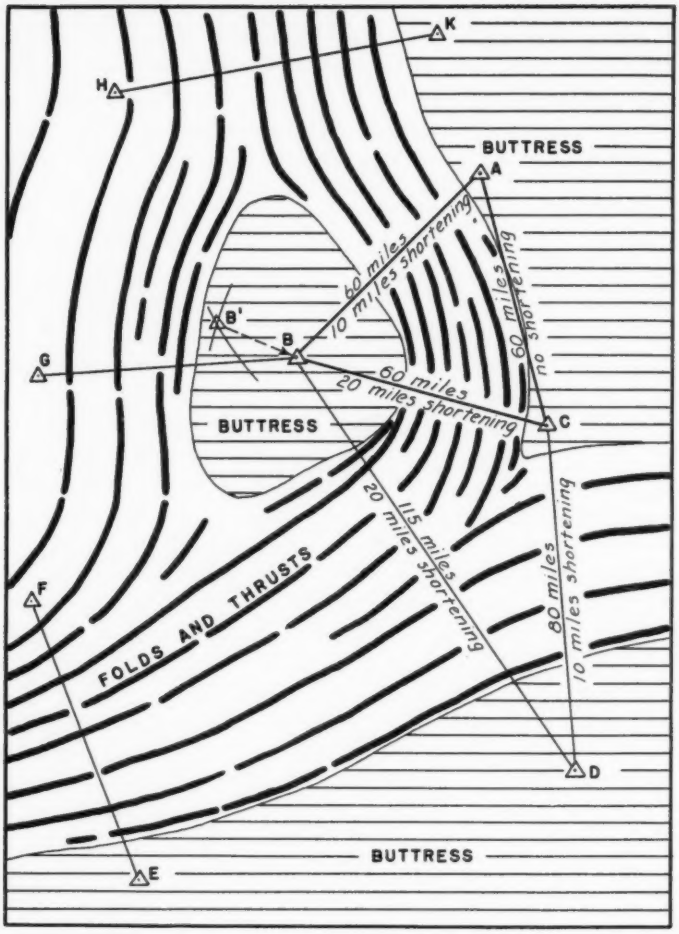

FIG. 1.—Assumed area of compressional structures showing simple net of sections for slotted templet.

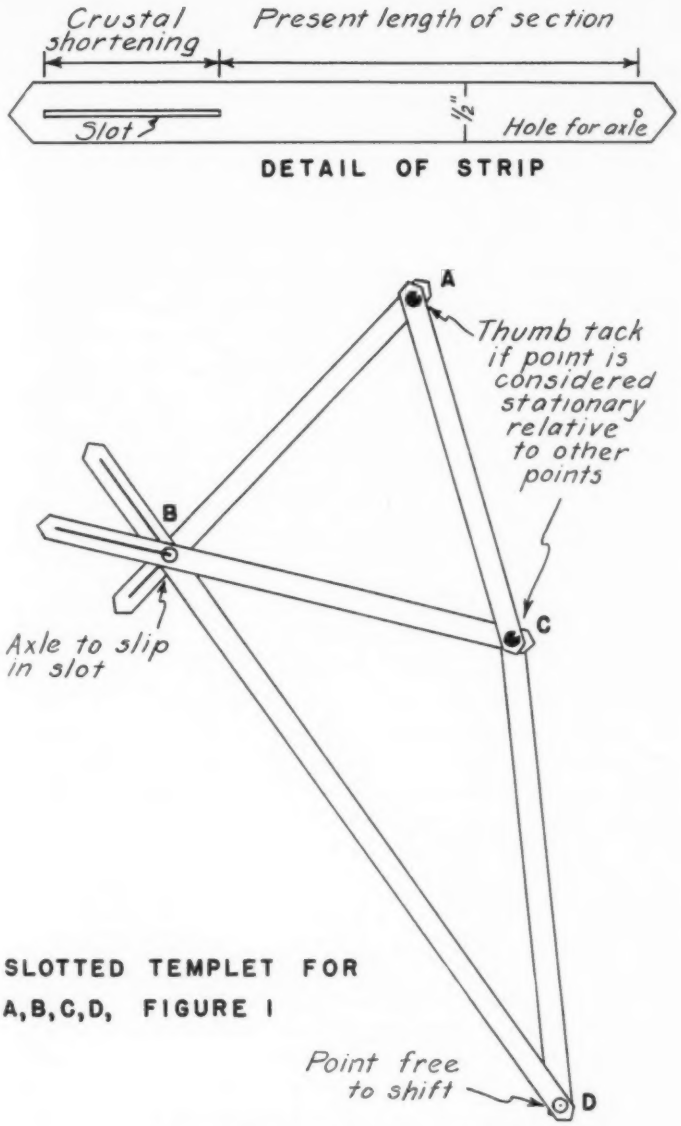

FIG. 2.—Plan for construction of slotted templet

triangles in the network are lacking, a certain amount of personal judgment is involved. The manner of adjustment in the example described below will serve to explain the general procedure in expanding the templet to the position representing the network of points before crustal compression.

THE WASATCH–GREAT BASIN REGION

A speculative but fascinating phase of a structural study of the Wasatch–Great Basin region is the question of crustal shortening during the Laramide revolution. After the structural elements had been compiled,[3] it was found that the folds curve through at least 270° of azimuth, and that a small buttress, the northern Utah highland, evidently had moved horizontally in relation to larger resistant elements—the Colorado plateau and the Wyoming basin (see Fig 4). The Uinta, Cottonwood, and Sheeprock uplifts complicated still more the structural setting.

In order to construct a slotted templet the amount of crustal shortening along a number of sections approximately at right angles to the immediate trend of the compressional structures first had to be estimated. Sections were chosen that best fitted analysis and, of course, where the data for estimation were available. The estimates of shortening were made by bending a copper wire along the line marking the Cambrian quartzite in the cross sections prepared for Plate I of the report on the structure of the Wasatch–Great Basin region.[4] The horizontal distance between the end points of the section was measured before and after straightening the wire. Where others had estimated the shortening, no additional estimate was attempted by the writer. Stratigraphic displacement and dip of thrust plane were used in calculating approximately the amount of shortening involved in thrust faults.

The templet was constructed on the scale of 1 inch to 6 miles in order to conform to a work map used by the writer. By superposing the templet on the map and anchoring the Uinta uplift, point *A*, with a pin, the rest of the model remained free to be adjusted to the various amounts and directions of shortening. The photograph of the templet, Figure 3, is a double exposure, made first with the

[3] Eardley, *op. cit.* [4] *Ibid.*

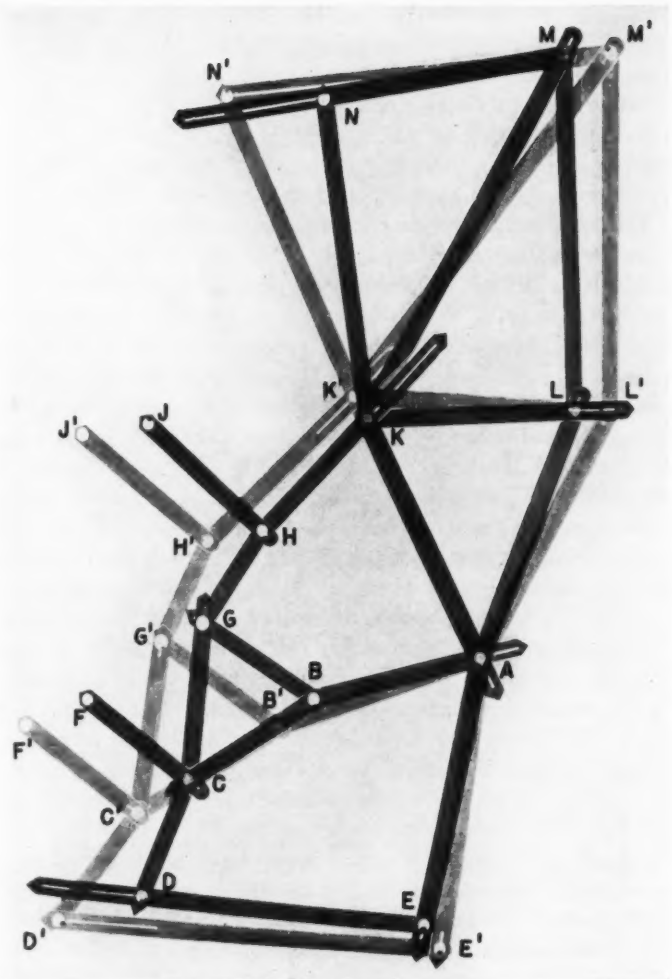

FIG. 3.—Slotted templet for the Wasatch–Great Basin region. The light strips show the extended arrangement and the dark strips the compressed. The red overprint of Fig. 4 corresponds to this templet.

templet set to represent the present condition of the earth's crust and then rephotographed after being pulled out to where the crustal points lay before the Laramide revolution. The pulled-out position is, within certain limits, a matter of choice, but the attempt has been made to arrive at one in which the various points along the west side all moved uniformly eastward. Within the net there was an unexpected but necessary movement of K' toward the southeast.

The templet brought to light a large error in the writer's first estimate of shortening through the Willard thrust sheets (strip H–K). This amount was originally set at 25 miles, but the templet could be adjusted in no way to satisfy this large amount and, at the same time, the other near-by displacements also. An amount of 13 miles harmonized best with the final setting, as shown in the red overprint of Figure 4 and the photograph of Figure 3. The original 25-mile slot in the H–K strip was left in the model and photographed in Figure 3 to illustrate the mechanical impossibility of a 25-mile amount of shortening through the Ogden Canyon section.

The network has a number of tie strips such as KN, KA, HG, and ML, which were sections either within the northern Utah highland or along the strike where apparently no, or little, shortening occurred. These tie strips were necessary to lend mechanical control to the apparatus and to eliminate as much subjectiveness as possible.

The best extended arrangement—that shown by prime letters in the red overprint of Figure 4—suggests that both the rigid area north of the Uinta uplift, the Wyoming basin, and the rigid area to the south, the Colorado plateau, moved about 2 miles west in relation to the Uinta uplift. Geological evidence to support this conclusion has not yet been found, but the suggestion seems worth recording. The most significant result of this approximate treatment of movements is the demonstration that in this region of diversely trending compressional structures the individual movements can all be resolved components of regional compression in one direction.

In reading an early draft of this manuscript Spieker[5] called attention to the risk involved in bringing the several orogenic episodes of late Mesozoic and early Tertiary time into one dynamic frame. As a result of his field work he finds that the Uinta uplift occurred

[5] E. M. Spieker, Ohio State University, written communication.

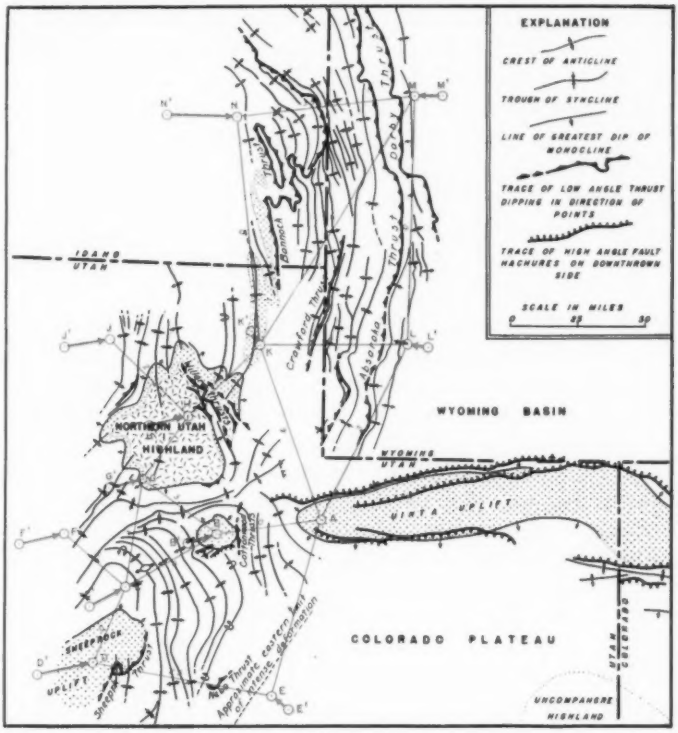

FIG. 4.—Structure map of the Wasatch–Great Basin region. The red overprint is the templet net according to which the direction and amount of movement of various points is indicated. The stippled areas are those of late pre-Cambrian and Cambrian rocks, chiefly quartzite; the hachured areas, those of early or middle pre-Cambrian rocks.

after or during the late stages of the folding in the Wasatch–Great Basin area. It is possible, therefore, that new and differently directed regional forces existed during the uplift of the Uinta arch. The consideration of an analogy, however, seems to warrant the assembling of the successive orogenic structures in this region under one mechanical treatment. As an ice floe is driven by a prevailing wind and becomes compacted, groups of cakes consolidate into large rigid masses. Mounting strain at points of greatest pressure results in failure and in sudden movement of certain masses from place to place and from time to time. Frequently the masses move at an angle to the regional deforming force or rotate as much as 90°, although the wind direction remains constant. A succession of orogenic episodes, if analogous to those in the compaction of a floe, could, therefore, result from one set of long-continued regional forces. The writer has found no stratigraphic or structural evidence that opposes this concept as applied to the Wasatch–Great Basin region, and since it is helpful to an understanding of the deforming forces of the region, it is presented as a working hypothesis.

A computation of the amount of areal contraction during the Laramide revolution within the limits of the net suggests that the original area was compressed 24 per cent.

CONCLUSIONS

The use of the slotted templet in resolving crustal movements is apparently sound, but the results are no more accurate than the estimates of crustal shortening along the several sections of the templet net. If most of the estimates are fairly accurate but one or two are not, these latter will be apparent immediately.

The diversely trending structural elements of the Laramide revolution in the Wasatch–Great Basin region may all be related to regional compression in an approximately east-west direction. The amount of shortening in the Willard thrusts appears to be about 13 miles and not 25 miles as originally estimated. The small buttress of the northern Utah highland has moved somewhat north of east and has shifted closer to the Wyoming basin and Cottonwood uplift.

ACKNOWLEDGMENTS.—Critical reading of the manuscript by T. S. Lovering and E. M. Spieker is appreciatively acknowledged.

REVIEWS

Prehistoric Life. By PERCY E. RAYMOND. Cambridge: Harvard University Press, 1939. Pp. ix+324; figs. 156. $5.00.

After twenty-five years of coaxing by students and colleagues alike, Professor Raymond has at last yielded and written a book, a gesture toward pedagogical orthodoxy which he often stoutly maintained he'd never make. But the stigma attached to his fall from grace is diminished by the fact that *Prehistoric Life* is no ordinary textbook. Rather it represents the 1939 status of the exciting and constantly changing series of lectures which Professor Raymond (in rank violation of the doubtless apocryphal Harvard tradition of "grandfather's lecture notes are good enough for me") has offered for many years under the prosaic title of "Paleontology 1." Unlike most texts, therefore, this one is not a catalogue of facts—it is rather a compendium of ideas.

That ideas feature so prominently in this book comes as no surprise to those who know Professor Raymond, for he fairly bristles with them. In his Introduction, however, he modestly disclaims direct responsibility, saying: "Acknowledgments . . . . are expected, and . . . . due. First and foremost I would place the twenty-five unfortunate classes on whom I have experimented. I have told them much that was not so, and made them learn theories which I have later abandoned. Questions which they asked led to ideas which I have since exploited as my own." But the author presents a truer picture of himself and of the growth of one of his concepts, when he says, on page 310:

> Fortunately man got down, or was driven down, from the trees before he became a monkey—"driven down," not by climatic changes, but because he was a more primitive, less competent, and less pugnacious animal than his associates. (This is an idea new to the writer, *having occurred to him in the few seconds since he began to write the previous sentence.* Perhaps man owes his present position to his inferiority to the other anthropoids; without large canines he could not fight, and his short arms and fingers made him an unsuccessful brachiator. . . . . As I frequently tell my students, the only way to orient oneself is by writing. Merely guide the nib, and ideas flow with the ink—not that the ideas are all good.)

Prehistoric Life is divided into twenty-nine chapters, only one of which, the penultimate, is directly concerned with plants. More significant still is

the fact that only eight of the chapters deal with invertebrate fossils, in whose study Professor Raymond has made so many outstanding advances. His restraint is particularly well shown in his discussion of "petrified butterflies," or trilobites, which he has limited to a scant eight pages despite the fact that he is the recognized trilobite expert and the subject itself is one of the most fascinating ones in the entire field of paleontology. This chapter terminates in a typical Raymondian touch: "Perhaps [the trilobites'] greatest contribution is the aesthetic pleasure the contemplation of their elegant shells has given to countless collectors and students of fossils."

The introductory chapters on "Fossils" and "Collecting Fossils" are admirably done, and the one on "Pre-Cambrian" life is an excellent recasting of Professor Raymond's definitive, but too little read, presidential address on the same subject before the Paleontological Society in 1935. The many problems involved in the origin of the chordates and in the vertebrate conquest of the land are penetratingly discussed in four chapters. The reptilian origin, advance, and decline are presented in five chapters, and the history of the birds in one. Seven chapters are devoted to the paleontological story of the mammals and man; and, of course, there is a final chapter entitled "Retrospect and Prospect."

Although this book obviously was designed as the basis for an elementary course in paleontology, few specialists will be able to read it without having their experience enlarged. The writer himself characteristically states that he knows that "many of [his] views are heterodox" and that various authorities "have offered criticisms and suggestions, not all of which have been accepted." The latter phrase is doubtless a magnificent understatement, as is his remark: "When I came to Harvard in 1912, I knew nothing about paleontology." But all teachers of the subject will sympathize with him when he says: "When I found I was expected to teach . . . . , I set out to learn something." That he was successful no one who reads *Prehistoric Life* will deny.

Is there anything wrong with this generally excellent and altogether charming book? Doubtless some will think so. The illustrations are well selected, but not so voluminous or so well reproduced as they might be. Moreover, many of them, which lack any scale whatever, will surely be misleading to beginners, and a number of the truly excellent drawings by L. Price and E. A. Schmitz were unfortunately reduced too much to show them off to their best advantage. But these are minor matters compared with the deliberate (and, in a work like this, perfectly understandable)

deletion of all bibliographic references—an omission which, from personal experience, this reviewer knows will not be regarded with kindness in all quarters.

CAREY CRONEIS

Erläuterungen zur geologischen Karte von Österreich und seinen Nachbargebieten ("Explanation of the Geological Map of Austria and Its Neighboring Countries"). By HERMANN VETTERS. Vienna: Geologischen Bundesanstalt (Geological Survey), 1937. Pp. 351, with tables.

This valuable book represents the compendium of years of experience and study by the staff of the Austrian Geological Survey, including such distinguished scholars as the author and his associates, Drs. Hammer, Beck, Spengler, Geyer, Waagen, Kerner-Marilaun, and Winkler-Hermaden. It is designed to accompany the map prepared between 1928 and 1933. The present scale of the finished map (1:750,000) affords an excellent overview of the principal features of the eastern Alps, and the limits of the map are happily extensive in that they cover a large part of southeastern Europe—most of that part included in the dual monarchy previous to 1919. The book here reviewed is essentially a stratigraphic and petrographic summary, a review of the literature in these domains and its bearing on the features shown on the map.

Perhaps one criticism, and only one, of the entire project may at first appear justified from the viewpoint of the foreign geologist: the features on the map are indicated in such detail that the larger stratigraphic divisions and sedimentary facies and the more significant structures do not stand forth. Thus, the great thrusts or *Decken* are not distinguishable so clearly as they would be on a more strictly tectonic map. The mineral deposits likewise are not highly conspicuous. Much the same may be said of the alpine glacial deposits. When it is realized, however, how well the map is adapted to a study of specific smaller regions, it becomes clear that this alternative purpose, undoubtedly of prime importance to most of its users, deserves precedence. The general treatment in the book is parallel with that of the map which it was designed to accompany.

Preliminary statements regarding the map are succeeded by detailed descriptions of the various formations, arranged primarily according to age and secondarily subdivided by regions. Some 280 pages are devoted to this part, the main body of the book. This is followed by a carefully annotated bibliography, including virtually all outstanding recent literature, a table showing the major time divisions, and a table of the "topo-

graphic" (or, more properly, cultural) symbols. An excellent index completes the volume.

Many items of interest might well be noted in an extended review. Brief mention may at least be made of the following. The extension in the use of the term "Flysch" to designate a sandy-clayey shore facies, in place of its restriction to a formation of specified age, is noteworthy. So also is the analogy between Alpine and Appalachian geology in the difficulties involved in dating the great intrusive masses, especially the granites; thus, the massifs of the Eisen Kappel-Veitsch regions can only be referred, despite the latest and most careful work, to the "post-Permian" and "pre-Miocene," much as, in similar circumstances, our Appalachian intrusions are regarded as of several ages, ranging from pre-Cambrian to Permian, and for much the same reasons. Likewise the Austrian geologists have found the correlation of the highly metamorphosed crystallines a difficult problem, reminiscent of the discussion in the United States as to the age of the crystallines in the region of the Martic thrust, and in general of the eastern border of the Appalachians. The recognition of an upper Cretaceous tuff-jasper-diatom series is also suggestive of the cryptocrystalline siliceous sediments of our West Coast. Among economic products, the iron ores of the Erzberg (pp. 180–81) and the mercury deposits of Idria (p. 157) merit and receive brief but useful descriptions. So also do the interesting salt stocks of the Lower Triassic in the Haselgebirge (p. 159).

Certainly, the regional geologist, concerned with the physiographic, stratigraphic, structural, or economic geology of Austria and adjoining parts of Yugoslavia, Hungary, Czechoslovakia, Germany, or Italy will find much of interest and value in this volume. That it and the map to which it refers could be completed during the troubled post-war period is a still further tribute to the firm devotion of its author and his colleagues to the cause of geology.

CHARLES H. BEHRE, JR.

Architecture of the Earth. By REGINALD ALDWORTH DALY. New York: D. Appleton–Century Co, 1938. Pp. xiii+211; figs. 152. $3.00.

The study of earth structure leads the student into speculations involving astronomy, chemistry, physics, engineering, geology, and geophysics. It implies an ability to weigh facts gained from the geologists' field studies with data from the laboratories of the experimental scientist, an ability to test inference and interpretation, and from the whole body of available

knowledge to create that hypothesis which best conforms to established laws in separate fields of the physical sciences. Of this type of brilliant synthesis and creative thinking R. A. Daly gives fresh proof in his new book, *Architecture of the Earth.* The material represents the slightly expanded lectures given on "The Crust of the Earth" under the auspices of the Norman Wait Harris Foundation of Northwestern University in May, 1937. The book forms one in the "Century Earth Science Series" published by the D. Appleton–Century Company.

In these lectures an attempt is made to report adequately for the general reader upon the author's contributions toward a philosophy of earth history which has been more fully defined in his earlier books, *Igneous Rocks and Their Origin* and *Igneous Rocks and the Depths of the Earth.* Although written with the general reader constantly in mind, the author does not exclude from his audience geologists and other scientists for whom this book will represent a summary of new field discoveries, the results of new research, and the modification or support that such discoveries and results exert on the author's theories of crustal zoning.

An ideal earth is imagined based on known data, and inquiry is made as to whether a planet so constructed should respond to forces as the real earth has already responded. Established facts are matched with reasoned or deduced behavior of the chosen earth model through geological time. Whether or not one agrees with the inferences and deductions that are made, one is never in doubt as to the reasons and bases for the author's hypotheses. An open mind is maintained toward other hypotheses, and his refreshing lack of dogmatism is evidenced in his readiness to change and modify his theories to agree with newly contributed facts from any field.

Chapter i presents the geologic field data which lend validity to the idea of density zoning of the outer solid earth. Chapter ii is concerned with the knowledge derived from seismic studies, the inferences that geophysicists have drawn from the speed of earthquake waves through the earth and from laboratory experiments in elastic properties of all accessible types of rock. These are found to check with the density shells of the earth model and extend the idea of density zoning to greater depths in the earth. The hypothetical model is next tested by a consideration of great mountain chains and the mechanics of their formation. Laboratory experiments on crystal deformation are reviewed and the suggestion is made that contraction and nonuniform folding of the crust toward the center of gravity is compatible with the idea of a model earth having a crystalline crust slightly heavier per unit volume than a vitreous

substratum of basalt. The inference is drawn that the structure and height of a mountain chain are both products of downward invasion of the substratum by solid crustal rocks.

In the next two chapters surface lavas and deep-seated intrusions are considered. The ascent and outpouring on the surface of basaltic lava is definitely related to density zoning of the imagined crust. Recent ideas about the origin of batholiths and their relation to the principal layers in the continental part of the earth's crust are reviewed, and the author's latest revisions of his own ideas on stoping, assimilation, and the mechanics of batholithic invasion are presented

The final chapter treats of the support of the earth's crust and discusses reasons for the maintenance of crustal relief in the light of isostatic speculations. The book is well illustrated by many carefully selected photographs and numerous line drawings of maps and figures that are an effective aid in clarifying the text.

According to the publishers, the book is intended primarily for use as a text in second-year college courses, but this should in no way deter the general reader who wishes a clear, logical, and interestingly written presentation of what one of the foremost geologic philosophers thinks of the structure of the earth.

J. T. STARK

Descriptive List of the New Minerals, 1892–1938. By GEORGE LETCHWORTH ENGLISH. New York: McGraw-Hill Book Co., 1939. Pp. 258. $3.00.

This book consists of an alphabetical list of species and variety names proposed since the publication of the sixth edition of Dana's *System of Mineralogy* which have been noted in the standard sources written in English. Besides the references are given in brief form a few data, including composition, properties, and localities; about ten names appear on each octavo page. It is thus a sort of dictionary of mineralogical names proposed in the last forty-six years. Corundum and quartz are listed only under "alpha," spinel only under "alkali," melanterite under "copper," etc. An index based on chemical composition should have been included. The book "is designed to save the busy mineralogist the hitherto necessary labor of hunting through much literature to find descriptions of new minerals."

D. J. F.